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DESIGN STUDY

10 MJ 10 TW STATIONARY FACILITY FOR PLASMA-FLOW DISCHARGE EXPERIMENTS WITH CURRENTS UP TO 25 MA

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Abstract

This work includes justification and the ideology chosen for 10 MJ facility for plasma flow discharge experiments with currents to 25 MA. With the current rise time about 1μs the facility has a power up to 10^{13}W. The application of a plasma current switch provides 100 ns current front in the load and a voltage about 2-3 MV. The facility may be used in experiments on the implosion of shells, to accelerate plasma toroids to 5-6 MJ and to generate electron beams by the voltage up to 2 MV and current to 10 MA. The work has been done under the contract № F6170894C0015 with EUROPEAN OFFICE OF AEROSPACE RESEARCH AND DEVELOPMENT.

Contents

Abbreviations

CS	capacitive store;	PFS	plasma-flow switch;
IS	inductive store;	PFD	plasma-flow discharge;
OS	opening switch;	MITL	magneto-isolated transmission line.
PES	plasma-erosive switch;		

Introduction

Further advancement of science in a field of high density energy physics, plasma physics, etc. tends to increasing experimental facilities power and energy store. Researchers attempt to obtain more extreme physical properties of materials, namely, density, temperature, specific energy density and energy flow. It is precisely here that one would expect to find new regularities, material properties and their applications in science and engineering. Technologies that allow to generate energy flows $\approx 10^{14}$ W/cm^2 are very complicated and expensive, therefore developers are searching for new approaches and procedures to create high-power energy sources for physical experiments with high density energy. By now, there are available a number of different technologies of high density energy physics wherein some parameters have record values. For instance, superhigh energy flows of 10^{18} W/cm^2 have already been obtained in focusing laser radiation on solid-state targets [1], but in this case energy store is only 1 J. Energy focusing by means of electron beams is not so successful, 10^{12}-10^{14} W/cm^2 [2]. Ion beams [3] and explosive magnetic cumulation [4] are also used for the same purpose. Capacitive stores are most widely used of all stationary laboratory facilities for energy storage and generation of high-power electric pulses.

1. Constructive features of high-power energy stores.

It is customary to split the energy stores into two groups. Provided that a capacitive store is not equipped with an electric pulse former it is called a capacitor bank, as it usually consists of a large number of single-type capacitors connected in parallel (or in parallel/series).

In facilities of the second type an intermediate former is used which is placed between a capacitive store (i.e. capacitor bank) and a load, and which shortens a current pulse front and increases facilities power transferred into the load. Clearly, that the loads for two types of facilities have essential differences and peculiarities. The most powerful capacitor banks (sometimes they are called "current generators") reach 100 MJ "NOVA" stored energy with 20 kV [5] voltage and 10 MJ "SHIVA STAR" with voltage 120 kV, power 10^{13} W and current up to 20 MA [6].

The second type of facilities may also be divided into two groups. There are traditional capacitive stores with forming lines (FL) [7, 8], and facilities with an intermediate inductive store (IS) and an opening current switch (OS) [9, 10].

Success achieved on facilities with forming lines is impressive. In the USA such large high-power facilities as AURORA, BLACK JACK-5, PROTO-II, PBFA-2, SATURN [12] have been developed and now they operate with 2-5 MJ stored energy, power up to 10^{14} W, pulse duration 20-50 ns, peak load current up to 10 MA, voltage 2-15 MV.

There is no fundamental difference between a capacitor bank and a forming line, as in either case the energy is stored in a dielectric's electric field. The chief merit of the forming line is in a short time of energy transfer into a load that at best is defined by the time of an electric wave passage along the line $t_i=2l/c_d$, where c_d - is the velocity of TEM wave in dielectric. Efficiency of energy transfer from the line is defined by a specific load and it has a maximum value at a load resistance $R_l=p$ - impedance of the line, and it only decreases when this condition is infringed. In actual design we failed to reach this condition and a load connected to the line usually has a complex resistance, and in the general case it is a line with distributed parameters, this fact abruptly decreases efficiency of facility and increases the time of energy transfer into a load.

All the above relates to a capacitor that also has sections (coats separated by dielectric) where energy with a volume density $\varepsilon\varepsilon_0 E^2/2$ is accumulated, as well as current-carrying conductors which are used for separate elements to be connected in parallel and/or in series into a bank. Inductive impedance is typical for these conductors, therefore capacitor as a rule has two characteristic parameters, namely, capacitance and inductance. As a consequence of a large number of conducting wires on the capacitor discharge, processes transform from a wave type to concentrated ones and are defined by its capacitance and inductance, and in this case they depend on geometry factors. The first value defines energy capacity and the second the time of energy output from a capacitor and its peak current.

Generally, a density of the capacitor's stored energy is 200 J/l [13], that is higher than that of the forming line (35-80 J/l) [14]. This is the main advantage of capacitors over forming lines that permits to reduce dimensions of facilities. Given above energy density of the forming line (FL) is obtained with the use of purified deionized water as a dielectric and, as the inevitability, pulse charging of the forming line from the primary capacitive store. Schematic of a facility with forming line pulse charging is shown in Fig. 1.1

FL characteristic charge time is $t_c \approx 1$ μs and one tries to decrease it, as this will increase an electric strength of dielectric and hence specific energy in the line, and for this purpose, additional water capacitors and FL are used.

Consideration of the forming line charging from a capacitive store and the line commutation into a load shows that energy is transferred from a capacitive store into the line during t_c, and from the forming line it is transferred in t_i Provided that energy losses are neglected and $W_{fl}=W_{cs}$, peak current I_{cs} of a capacitive store is smaller than an output current of I_{fl} line by a factor of t_c/t_i.

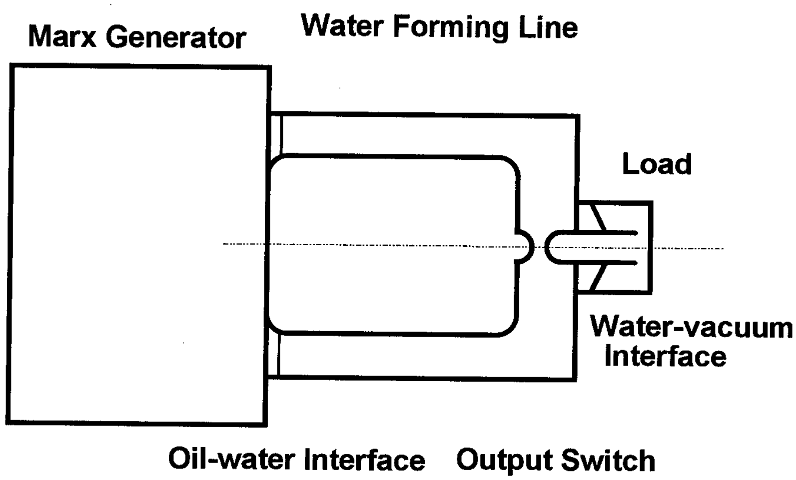

Fig. 1.1. Schematic of a facility with a water forming line

Presently this technology is developed very well that is confirmed by available facilities and those being built. Energy capacity and power of these systems are increased by parallel switching the forming lines onto a load with forming lines placed on circumference around the load. As in a capacitor, here we encounter a problem of the forming lines parallel connection, since this connection is purely inductive and extends current rise time into a load. It should be pointed out, that these facilities used as loads often assume an electron or ion diode, and then every line will have its own diode and a problem of delivering to a target a large number of converging electron or ion beams takes on great significance.

When using as a load imploding plasma shells, metal foils or arrays of wires, gas puffs and Z-pinches, the energy supply to the load and the load itself are of inductive nature and extend the current rise time. To summarize, we can say that drivers of plasma loads based on forming lines have such drawbacks as;

design complexity;
small energy density;
large size;
high cost.

Should a plasma load is examined as a whole, we can say that all these loads convert the current magnetic energy, delivered into a load by a driver, into intrinsic plasma energy which becomes a powerful radiation source. Thus, the major driver feature should lie in the ability to provide maximum density of magnetic energy in a load that evidently is related to the attainment of the greatest possible current in a minimum possible time.

That is, the driver of a plasma load must be a current driver or a current generator. As for the load, the method of a current pulse generation is of no significance, if only it has necessary amplitude and time characteristics.

Let us turn back to capacitive energy stores. Achievements in current opening switches have made it possible to form multi-megaampere fast-rising current pulse [5]. Schematic of this arrangement is shown in Fig. 1.2.

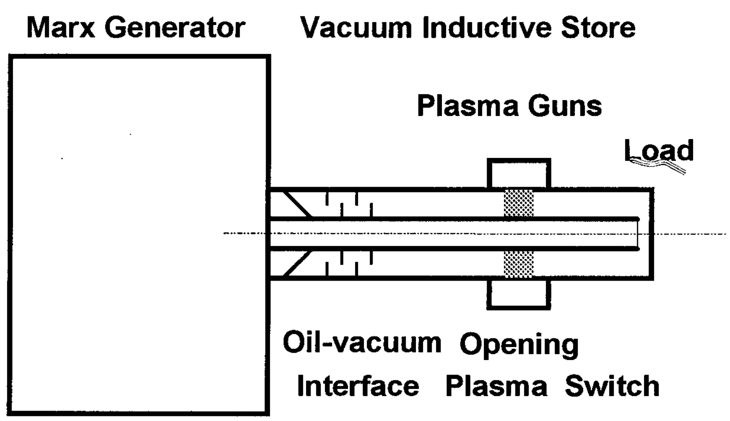

Fig. 1.2. Schematic of a facility with an inductive store and a plasma opening switch.

On a capacitive store operation an inductive store is energized through a current opening switch. At the instant magnetic energy peak $W_{mag}=LI^2/2$, where L - is the store inductance, I - is the store current, resistance of a current opening switch abruptly increases and in a very short time the current from the opening switch is commutated into a load which is connected across a current opening switch.

In this case we have a structural scheme of a facility wherein a forming line is replaced by an inductive store with a current opening switch. The energy is stored in a current magnetic field. Energy density in an inductive store is defined by value $\mu_0 H^2/2$ which may reach >100 kJ/l for a store made of standard conductors. In vacuum inductive stores of a microsecond range a value of 2 kJ/l has been obtained, that is 20 times more than that of a water forming

line. As a result the store size is sharply decreased. Plasma-erosive opening switch (PES) [6] and plasma-flow switch (PFS) [17] are used as current formers-opening switches.

The first two types of switches are most widely used, and plasma-erosive opening switches were used in facilities with forming lines for the first time, that made possible significantly sharpen current pulses in the load and eliminate prepulse voltage. Then some attempts were made to study and to use PES for long time powering [5, 18]. In VNIIEF facility "PIRIT"-2000 has been built with energy store up to 2 MJ and current about 7 MA. The PES are successfully used for powering time of ≈1 μs, and it reduces a load current rise time by a factor of 10-20 and increases voltage about 5 times.

Researchers from the Phillips Laboratory (AFWL) investigate the ways to sharpen megaampere currents with 4-10 μs rise time. They proposed and have studied plasma-flow opening switch [7]. This switch possesses high factors of voltage increment (up to 10) and current duration reduction (about 20), as well as high efficiency of current transfer (80-90%) from a store to a load. To carry out investigations they use multi-megaampere facility SHIVA-STAR. Plasma-flow switch is used at currents over 10 MA and energy storage of an inductive store more than 5 MJ, it provides ≈200 ns current rise time in a load [7].

Comparison of PFS and PES processes shows that in PFS there are two phases of work. The first stage is the inductive store powering when a ring plasma shell is accelerated in a vacuum coaxial inductive store. Time required for powering is provided by choice of the PFS shell initial mass, then the shell at a high speed passes by the corner of the central coaxial conductor where the movement of plasma becomes purely two dimensional, and a phase of the resistance sharp increasing comes. We believe that at this point the main plasma feature, its density, dynamically decreases to such values that mechanisms of plasma erosion start working and this results in fast increment of resistance and current breakage through plasma with switching it to a load. Since processes and nature of plasma flow in PFS are as minimum two-dimensional, theoretical interpretation of PFS processes can be realized only by numerical calculation, as it was done in [19] using MACH2 program.

To summarize consideration of the current opening switches features of megajoule megaampere inductive stores one can state, that by now, researchers possess sufficiently developed technologies to realize a design of 10 MJ facility with an inductive store and high-power current opening switch. This design of a high-power $P=10^{13}$-10^{14} W machine for plasma loads investigation has a number of advantages over the forming lines:

small size of an inductive store and an opening switch;

larger values of the currents obtained;

simplicity of a design;

low cost.

As noted above, with the same capacitive stores the volume of an inductive store is 20 times smaller than a forming line, that is why researchers should focus their attention on the circuit with an inductive store.

Let us consider peculiarities of the scheme with an inductive energy store. The main difference is in characteristics of a capacitive store. In case of a forming line the capacitive store charges a line in 1μs, that is transfers the stored energy into the line's capacity which is commutated into the load by a switch. Evidently, since the peak voltage of a capacitive store is equal to a forming line voltage and to a voltage of the load (for a single forming line), the peak current of the line charging, i.e. capacitive store current, will be $I_{cs} = \frac{t_i}{t_c} I_{fl}$, where I_{fl} - is the line output current, t_i - is load current rise time, t_c - time of a line charging form a capacitive store. This expression points up to a fundamental property of a forming line, it is a capacitive store multiplier of current and power.

In case of an inductive store, on operation of a current opening switch, the current is delivered to the load (complete deliver is preferable), therefore the current rise time in a load should be reduced and this results in a voltage increment at the load as compared to the capacitive store peak voltage (usually up to 2-5 times. Thus, opening store in the facility is "a multiplier of voltage and power".

The foregoing requires that the capacitive store provides in the inductive store current > to the required load current in the charge time $t_c \approx 1$-2 μs. It means, that the capacitive store should be a current generator-capacitor bank. Time required for an inductive store charging must be ensured by the bank' power (bank voltage). The achievement of this requirement becomes more complicated with the capacitive store energy increment, as this will cause the increase of a store' size and current transmission line from a CS separate module to an inductive store (IS), as well as an inductive current rise. As we have already mentioned, this will cause the energizing time increase and the peak inductive store current decrease. To avoid this, it is necessary to increase the CS voltage with increasing the CS energy in order to compensate the increment of a current transmission line inductive fraction in total inductance of the circuit.

The essential feature required of all facility elements (CS, transmission line, IS and opening switch) is that a minimum possible inductance must be ensured to keep up the necessary current and time of IS powering with the energy store increment. It is also desirable that CS inductance and transmission line inductance would be smaller than that of IS.

Thus, CS of a facility with the current former differs from CS of a facility with a forming voltage line in that it has higher output current, low output voltage and higher capacity at the same energy store. Requirements on the reduction of the transmission lines length compel one to use more tight arrangement and to choose an optimal voltage of CS.

2. Analysis of the inductive store efficiency with a plasma load.

Eventually, in operation of a facility the energy from a volume of the capacitive store is transferred along transmission lines and throughout an opening switch into the load. Let us consider an inductive store circuit shown in Fig. 2.1. Assume that an opening switch S_0 (OS) comes into action at CS peak current, then from this point capacitor capacity may be thought as short-circuited, since the time of the current switching off is much less than a period of a circuit oscillations.

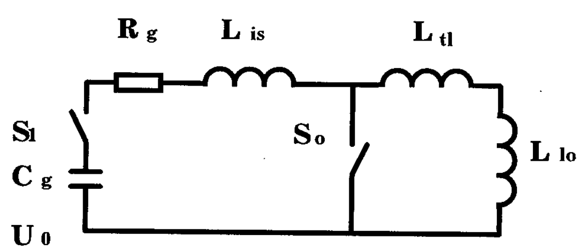

Fig. 2.1. Equivalent network of a discharge circuit.

An opening switch S_0 is parallel-connected with a plasma load $L_{lo}(t)$ by means of a transmission line with L_{tl} inductance. To consider the key energetic characteristics without using numerical calculations, let us assume that resistance of the switch S_0 becomes large reasonably quickly in comparison with a circuit impedance, and that there are no active energy losses in the circuit (R_g=0). Then from the flux conservation law Φ=LI=const we have an initial energy $W_0 = \frac{CU^2}{2} = \frac{\Phi^2}{2L_{is}}$, in the inductance L_{is} with a flux Φ. After the functioning of an opening switch energy in the overall circuit will be:

$$W_1 = \frac{\Phi^2}{2(L_{is} + L_{tl})} \tag{1}$$

and after implosion of the shell:

$$W_2 = \frac{\Phi^2}{2(L_{is} + L_{tl} + L_{lo})}. \tag{2}$$

The rest of the IS energy will be used to execute work with an imploding plasma. The energy transformed into the shell kinetic energy, which at the collision of the shell on a load axis will transfer into intrinsic plasma energy and will be converted into radiation of a hot dense plasma, will be Wk=W1-W2. Thus, we obtain:

$$W_K = \frac{\Phi^2 L_{lo}}{2(L_{is} + L_{tl} + L_{lo})(L_{is} + L_{tl})}. \tag{3}$$

If $\Phi^2 = 2W_0L_{is}$ is substituted, then we have:

$$W_K = \frac{L_{is} L_{lo}}{(L_{is} + L_{tl} + L_{lo})(L_{is} + L_{tl})} W_0. \tag{4}$$

We consider L_{lo} to be a volume inductance for which an initial volume of the shell is decreased, and assume that in compression the symmetry and cylindricity of the shell will be conserved. From expression (4) it is clear that at $L_{lo} >> L_{is} >> L_{tl}$ the overall magnetic energy of an inductive store may transfer into a shell energy. Inductance of the imploding shell is defined by:

$L_{lo} = \frac{\mu_0 \ell}{2\pi} \log \frac{r_1}{r_2}$, where $\mu_0 = 4\pi 10^{-7} \frac{H}{m}$, l- is the length of the shell, r_1, r_2- are initial and final radii of the shell, so L_{tl} may be increased by increasing the length l or relation $\alpha = r_1/r_2$, with a logarithmic dependence of the load final inductance on a. Unfortunately, a large number of purely physical factors such as instabilities of a shell form, shell heating by the current, final thickness of a plasma shell may account for a situation when in experiments we have to deal with $\alpha \approx 10$-15. This value is determined by X-ray radiation and for a current layer it may be grossly overestimated, but even then $\mathrm{Log}(\alpha)=2.3$-2.7.

In actual designs of imploding shells an initial radius $r_1=1.5$-5 cm, length is $l=2$-5 cm. The time of the shell implosion is $t_{im}=40$-200 ns, and the time of X-ray radiation is 20-100 ns.

We emphasize that from physical point of view an imploding shell itself is a power sharper as it is accelerated at a distance = r_1, but deceleration and thermalization, i.e. energy conversion from kinetic to thermal and then to radiation take place on the way = r_2, i.e. approximately 5-10 times more intensive than electric power is applied to the shell.

Experiments on the shells implosion at different time of acceleration, which were conducted in many high-power facilities, showed high efficiency of

the method of energy concentration and conversion of CS energy into the energy of X-ray radiation (up to 20% of the energy stored in CS) [17].

In evaluating L_{lo} value for a real load a value L_l=20 nH may be obtained, but for an inductive store with $L_{lo}=L_{is}$ and $L_{lo}>>L_{tl}$ expression (4) shows that a half of the CS energy may be evolved in plasma. Let us consider condition $L_{tl}<<L_{lo}$=20 nH, it is clear that it defines the quality of transmission line from an opening switch to the load.

Inductance L_{tl} is a geometry factor, so minimum inductance may be obtained only in case when OS is placed near the load, i.e. OS dimensions should be of the order of the imploding shell size. Current pulse shouldn't be transferred at a long distance, this may cause large energy losses and reduction of a facility efficiency.

The time of a shell acceleration t_{im} and duration of X-ray radiation experimentally have the following dependence: $\tau_r \cong \frac{t_{im}}{5}$. And as a consequence, experimenters are trying to decrease t_{im}, that is usually chosen to be of the order of the load current rise time, and it is generally decreased by increasing an opening switch voltage applied to the load, i.e. $U_{lo}=L_{lo}dI/dt$.

3. Analysis of plasma opening switches for inductive stores.

At present plasma-erosive and plasma-flow switches [26, 32] are most widely used to commutate CS current.

Plasma-erosive switches (PES) are more actively engaged in nanosecond accelerators to eliminate voltage prepulse and to increase facility's power. Serviceability of PES has been tested in a microsecond range as well, with the time of IS powering ≈1μs. But in this case PES works at the intensity of a magnetic field no more than 210^6 A/m (B=2.5 T) [15]. This value may be increased by decreasing time powering, i.e. in a microsecond range plasma drift caused by magnetic pressure is increased towards a load. And this fact severely restricts application of PES in high-current (I>5 MA) facilities using Z-pinches and plasma shells as a load, because of the discrepancy between dimensions of PES diameter ∅=1-2 m and that of the load ∅<10 cm, and, as a consequence, high inductance L_{tl} between PES and the load.

Employees of Phillips Laboratory have offered and studied a plasma-flow switch operating with a magnetic field intensity H=210^7 A/m (B=25 T), that is by the order of magnitude higher that for microsecond PES. And this made possible to extend a field of application for plasma opening switches into a range of still longer powering time, to decrease the switch dimension to a load

size and to obtain good transfer of current and energy into a plasma load [17]. In these experiments the current in IS reached 12-13 MA at 3.5-4 μs. Constructive scheme of IS with a plasma-flow switch is shown in Fig. 3.1. Plasma-flow switch represents a plasma circular jumper between coaxial electrodes. Under a pressure of a magnetic field it is accelerated towards a load and at a distance of 7,5 cm it reaches velocity of 7 cm/μs. In plasma ring passage by the corner of the central electrode there takes place current transfer onto a load which is situated on a diameter being smaller then a diameter of the central IS conductor. In experiments with SHIVA STAR facility the time of current transfer t_{lo}=300 ns and 80 % current transfer were obtained.

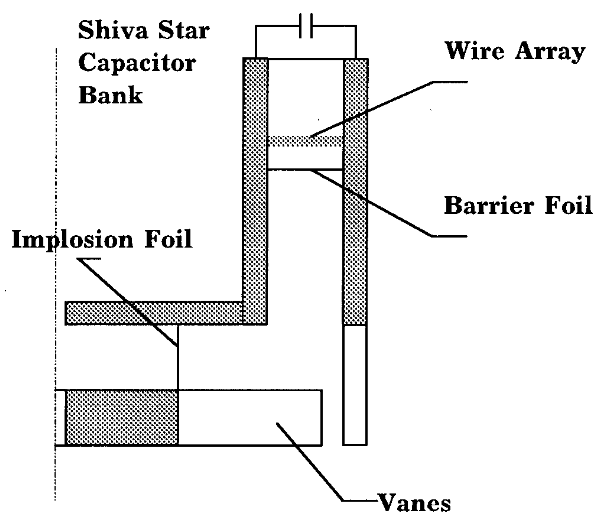

Fig. 3.1. Constructive circuit of the SHIVA STAR plasma-flow switch.

SHIVA STAR plasma-flow switch allowed to reduce CS current front from 3.5 μs to 0.3 μs, i.e. about 10 times, and this testifies to a good switching quality of these switches. Let us assume that this feature of PFS is invariant relative to the powering time, then reducing time of powering to 1 μs one may expect decreasing of a current rise time in a load up to 100 ns on keeping high inductance B>25 T. This places facilities with PFS at a level of parameters of facilities with forming lines which are incomparably more complicated and larger.

An essential parameter which affects the time of PFS switching is the velocity of a plasma shell and its thickness, more precisely, the thickness of a current layer in a plasma shell. The time of a current switching from the shell to a load may be roughly estimated by the flight time of the shell past the load $t_{lo}=l/v_{sh}$ where l-is the length of the load, v_{sh}-is the shell velocity.

To obtain short switching time one should try to increase the velocity of a plasma flow. At the same time, if you obtain high velocity of plasma escape from a coaxial gun, it means that during powering plasma will pass a long way, i.e. inductance of a discharge circuit will be highly increased and that will cause severe drop of magnetic energy and decrease of the energy delivered into the load. Hence, all spatial and time characteristics of PFS are closely connected with a facility energy parameters, and to choose more precisely these dimensions, mass of the shell as well as to calculate electric features one should use a numerical calculation technique for equations of a discharge circuit and acceleration of a shell mass by magnetic field of IS.

3.1. Analysis of a shell acceleration by the current of a capacitive store.

Let us consider a discharge circuit of CS with a coaxial inductive store being electrically short-circuited by a circular plasma shell with the mass m. Electrical circuit is given in Fig. 3.2.

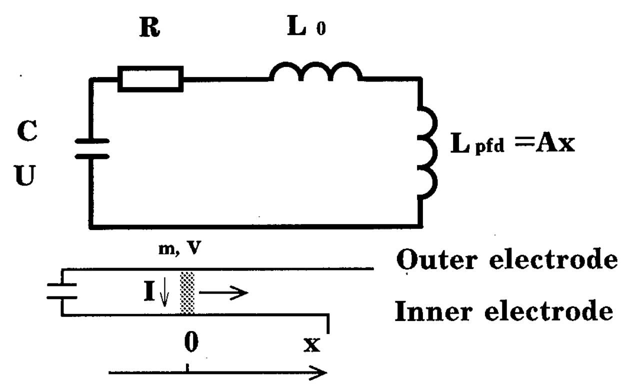

Fig. 3.2. Electric network of PFS powering circuit.

C, L0 - are capacitance and inductance of CS to the place of a plasma jumper location. $L_{pfd}(t)=Ax(t)$ - is the inductance of the path traveled by a plasma shell in time t after the emergence of current in a circuit, A- is the inductance per unit length of coaxial. A shell with mass m experiences a force acting on the side of the magnetic field, which is given by the following equation:

$F_{mag} = -\frac{\partial W_{mag}}{\partial x}$, where x - is the coordinate along the way of the shell acceleration. Since $W_{mag} = \frac{\Phi^2}{2(L_0 + Ax)}$, here Φ- flux is independent of x, then $F_{mag} = \frac{A\Phi^2}{2(L_0 + Ax)^2} = \frac{AI^2}{2}$. Current I of the circuit is determined from the equation for voltages at the circuit sections:

Uc=Ul+Ur,

where Uc=Q/C, $U_l = \frac{d}{dt}((L_0 + L_{pfd})I)$ and U_R=RI, Q - is the capacitor charge, R - is the resistance of the circuit.

Inductance Lpfd is determined from the equation of the shell motion under the action of magnetic pressure:

$$\frac{d^2x}{dt^2} = \frac{F_{mag}}{m}$$

For simplicity's sake, we shall not consider magnetic pressure dependence on the shell radius that in actual practice causes the shell's deflection from the vertical position. These two equations are reduced to a set of equations of the first order:

$$\frac{dx}{dt} = v \qquad (1)$$

$$\frac{dv}{dt} = \frac{AI^2}{2m} \qquad (2)$$

$$\frac{dI}{dt} = \frac{1}{L_0 + Ax}\left(\frac{Q}{C} - (Av + R)I\right) \qquad (3)$$

$$\frac{dQ}{dt} = -I. \qquad (4)$$

With initial conditions x(0)=0, v(0)=0, I(0)=0, Q(0)=CU. In these undimensional equations x - is the coordinate of a plasma jumper, v - is its velocity, I - is the current in the circuit, Q - is the capacitor charge. The variables of this system can be transfer to dimensional variables by the next multipliers: $Q_0 = CU_0$, $t_0 = \sqrt{L_0C}$, $x_0 = \frac{L_0}{A}$, $v_0 = \frac{x_0}{t_0}$, $I_0 = \frac{Q_0}{t_0}$, $R_0 = \sqrt{\frac{L_0}{C}}$, and $m_0 = \frac{CU_0^2}{v_0^2} = \frac{CA^2}{L_0}2W_0$. The system solutions depend on one parameter m (if R=0). The system of equations was solved using numerical techniques for values Uo=1, Lo=1, C=1, m=1, A=1 and R=0. Further one or several parameters of m_0 were varied in order to find an optimal relation between these values. Using these values of parameters simplifies analysis and reveals major tendencies and the dependence on the circuit parameters. PFS powering is an important part of

CS operation that directly effects on PFS plasma velocity and on a distance traveled by a plasma washer. Main discharge values are given in Fig. 3.3.:

$W_{mag} = (L_0 + Ax)I^2 / 2$ is the magnetic energy of the circuit;

$W_{kin} = \frac{mv^2}{2}$ - is the plasma kinetic energy;

$W_{el} = \frac{Q^2}{2C}$ - is the electric energy in capacitor;

I(t) - is the circuit current;

x(t) - is the shift of the shell;

L=Lo+Ax(t) - is the circuit inductance.

v(t) - is the plasma velocity for the shell mass m=0.1.

The energy values are normalized to an initial capacitor energy W=0.5. The calculations show that the moving plasma shell affects a discharge circuit as an active resistance, with an electric energy from the capacitor being converted into a plasma kinetic energy, but the higher plasma velocity, the higher voltage is on it U=AvI and this results in the reduction of the peak current in a circuit and in the increment of the energy left in the capacitor.

It is reasonable that the point of a discharge circuit switching off is chosen in a maximum of the current or magnetic energy. In case of PFS powering with an increasing inductance, current maximum occurs earlier that of magnetic energy and the latter will further increase due to the increment of the PFS inductance.

Because of this, we performed calculations of Wkin, Wmag, x, v at maximum Wmag and maximum current Imax in relation to parameters of a circuit and plasma mass. In Fig. 3.4. these values are given as a function of an accelerated shell mass. It is worth noting that in case the shell doesn't move (m=∞), the current maximum would be at the instant of time $T/4=\pi/2=1.57$. As evident from the charts mass m has been varied from 0.01 to 1 and the values relating to the magnetic energy maximum Wm are more important than analogous values for the current maximum Im. The energy dependence Wkin(m) is considered to be of interest. Its value is not greater then 0.23 of the initial energy and it changes by a factor of 10^2, i.e. it has a weak mass dependence. Increment of the shell mass primarily causes the increase of the energy stored in magnetic field and the reduction of energy left in capacitor. The calculations show that if the maximum magnetic energy Wm is given by a certain value, then from the charts one can uniquely determine the mass of the shell m, distance x for which the shell is shifted, its velocity and a point of time t_{max}.

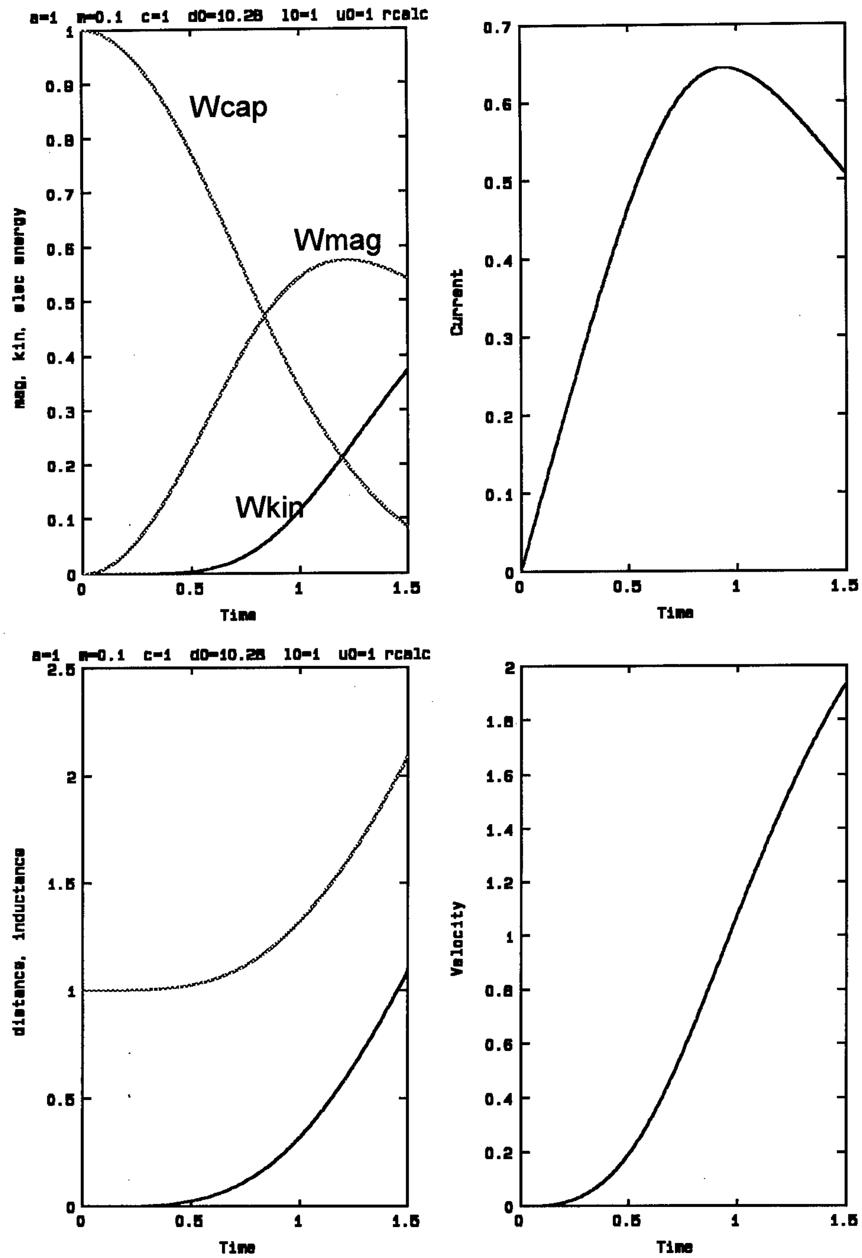

Fig. 3.3. The results of temporal dependencies calculation for m=0.1.

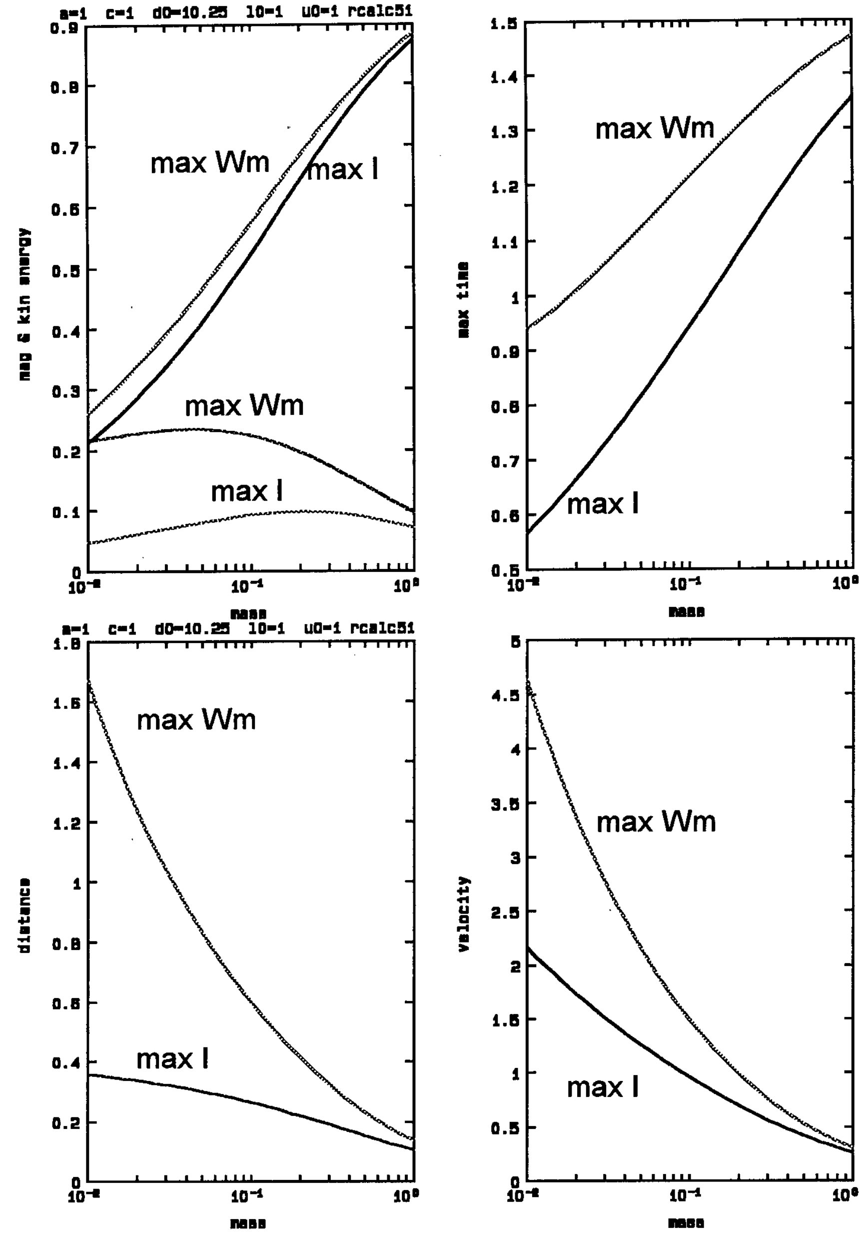

Fig. 3.4. Circuit characteristics as a function of mass.

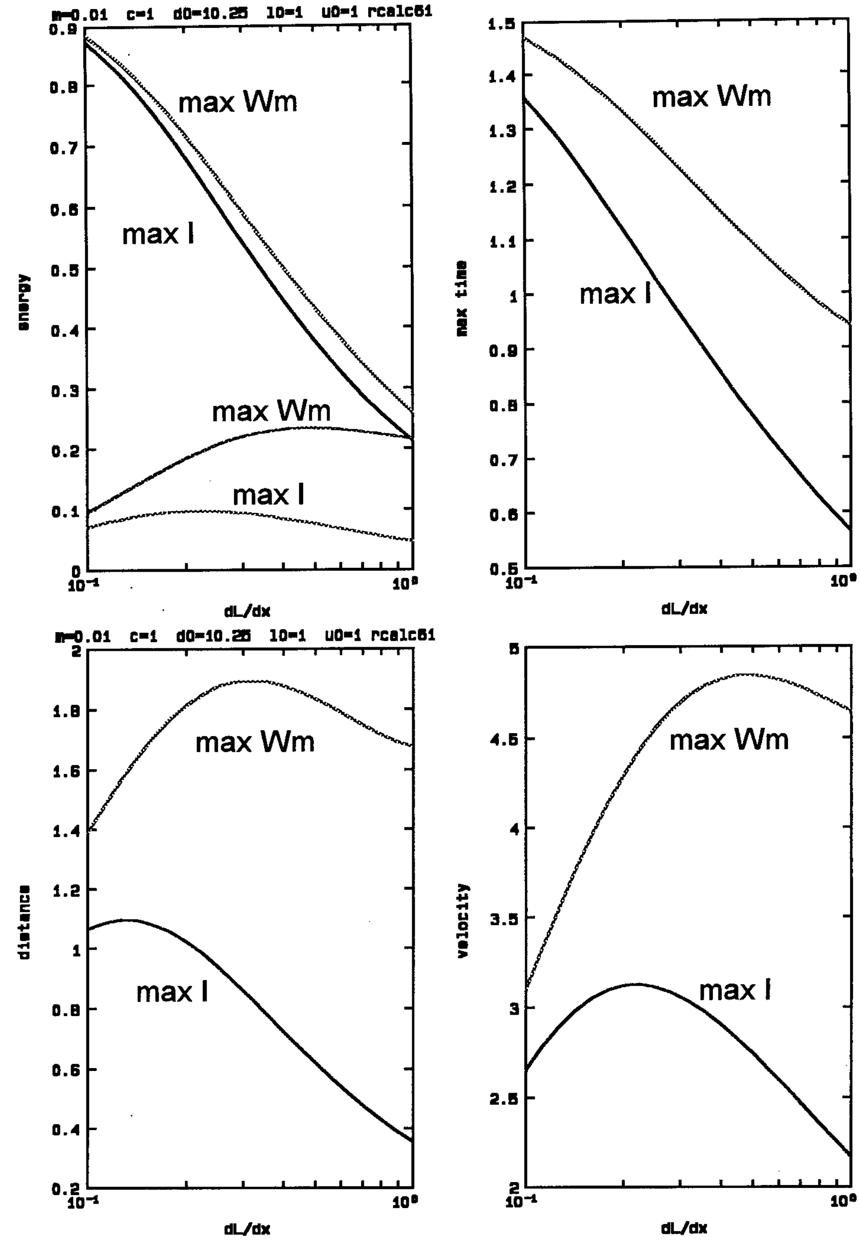

Fig. 3.5. Circuit characteristics vs. A - inductance per unit length.

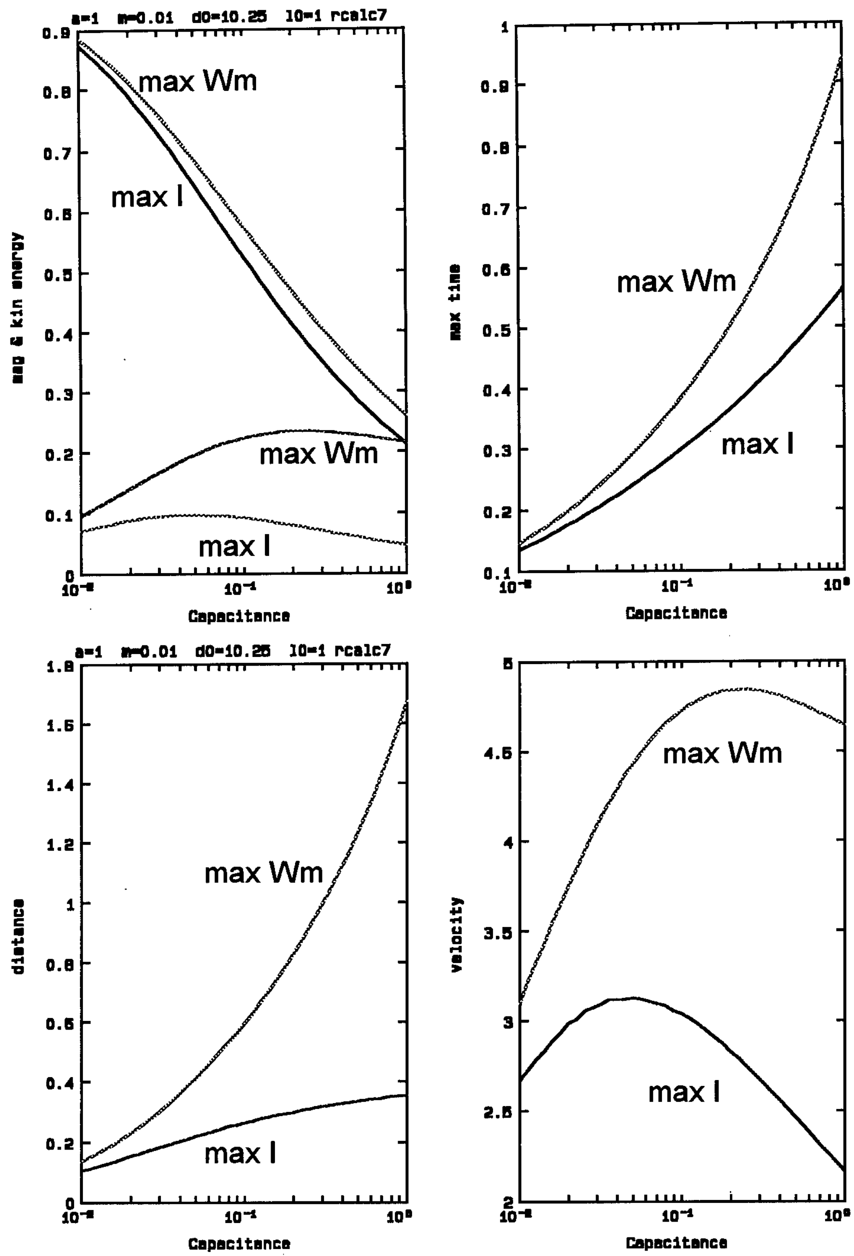

Fig. 3.6. Circuit characteristics vs. capacitance.

Value A=dL/dx is a very important parameter. For coaxial geometry it is determined by expression $A = \frac{\mu_0}{2\pi} \ln\frac{r_2}{r_1}$. In Fig. 3.5. you can see the principal values as a function of A. Notice that the plot of energies is the mirror agreement of an analogous one shown in Fig. 3.4., but value of A changes from 0.1 to 1, and m - from 0.01 to 1, i.e. by an order of magnitude and by a factor of 10^2, respectively. On the whole one may see that decreasing A it is possible to increase energy up to 0.9 and to obtain high plasma velocities v=3-5 at the distance of acceleration being practically constant x=1.4-1.9. As compared with results of Fig. 3.4., it is possible to obtain velocities by an order of magnitude higher with about the same kinetic energy and magnetic energy of 0.9. From this follows the conclusion that A affects IS energetic in a similar way as $1/m^2$.

Main parameters of PFS circuit are shown in Fig. 3.6. as a function of a capacitor capacitance C. Capacitor voltage U0 was changed according to the law $U(C) = \frac{1}{\sqrt{C}}$, in order to determine capacitance effect at constant CS energy $W_{el} = \frac{Q^2}{2C}$. From the plots of energy and the distance we see that W and x have just the same dependence on C as on 1/m (see Fig. 3.4.) and with the same magnetic energy velocity v is about 10 times higher, while capacity is decreased up to 0.01.

Analyzing dependence of the peak magnetic energy in a store one may draw a conclusion that it is desirable to obtain minimum kinetic energy of the shell, then nearly overall CS energy will be converted into IS magnetic energy and will take part in switching onto the load. It means that circuit current will approach the current in the circuit with initial parameters L_0, C, then the set of equation may be solved with $I=I_0\sin(\omega t)$ and the equation of motion $\frac{d^2x}{dt^2} = \frac{AI^2}{2m}$ may be solved for given I. Thus, $I_0 = U\sqrt{\frac{C}{L}}$, $\omega = \frac{1}{\sqrt{LC}}$ then the shell velocity is obtained upon integrating (2) with respect to the time:

$$v = \frac{AI_0^{\,2}}{4m}\left(t - \frac{\sin(2\omega t)}{2\omega}\right). \qquad (5)$$

If the velocity is once more integrated with respect to the time, we have:

$$x = \frac{AI_0^{\,2}}{8m}\left(t^2 - \frac{\sin^2(\omega t)}{\omega^2}\right). \qquad (6)$$

If consider the point of a current maximum that occurs at $t_m = \frac{\pi}{2\omega}$, at that instant the shell will have velocity:

$$v_m = \frac{AI_0^2 t_m}{2m} \tag{7}$$

Going to another values we obtain:

$$v_m = \frac{\pi A}{4m}\sqrt{\frac{C}{L}}W_0, \tag{8}$$

where W_0 - is initial energy of the store.

At this time a value of the plasma shell shift will be: $x_m = \frac{\pi^2 - 4}{8\pi^2 m} AI_0^2 t_m^2$,

substituting v_m from (7) we have:

$$x_m = \frac{\pi^2 - 4}{2\pi^2} v_m t_m, \tag{9}$$

$$x_m = 0.3 v_m t_m$$

Thus, velocity and distance are associated with the point of the current maximum. If v_m and t_m are expressed in terms of the circuit parameters, well obtain:

$$x_m = \frac{\pi^2 - 4}{16m} ACW_0 \tag{10}$$

Let us return to the initial condition under which we have found these solutions, they are $W_{kin} << W_{mag} = W_0$. Consequently, solution of (8) must obey this condition, then substituting values of v_m we obtain limitation by value A:

$$A^2 \ll \frac{32Lm}{\pi^2 CW_0} \tag{11}$$

This condition connects A and m to ensure practically complete transfer of energy from CS to IS and the field of application of solutions (8) and (10). If condition (11) is checked for solutions in Fig. 3.4.-3.6., so even at best for m=1 corresponds A=1<<6.2 and gives values of v_m=0.3927 and x_m=0.1834 that are 20% excessive (must be 0.3102 and 0.1390 respectively).

Condition (9) is fulfilled more exactly than (8,10) even at m=0.01, though condition (11) is not met. For the current maximum and W_m maximum it is fulfilled with an accuracy to 3% and 25%, respectively, this is shown in Fig. 3.7. where $\frac{x_m}{v_m t_m}$ is given as a function of a shell mass, obtained at the points of W_m and I maximum. This allows one to consider it true for the case with maximum losses of CS energy for kinetic and electric energy.

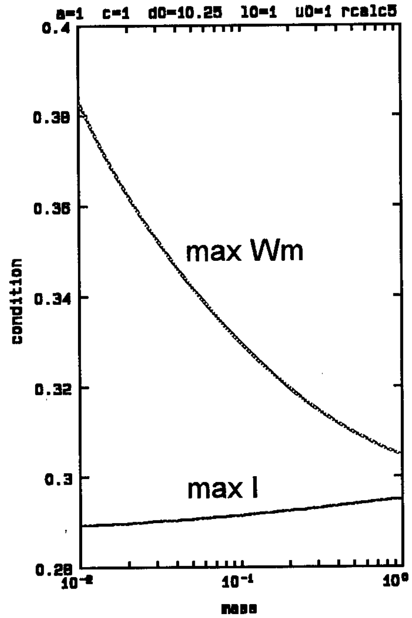

Fig. 3.7. $\frac{x_m}{v_m t_m}$ dependence for max W_m and I_m.

In principle, field of application of formulas (8) and (10) may be expanded if a correction factor is introduced, but this doesn't change the regularities. The exact solution may always be found by numerical technique, though numerical solutions are more difficult for analysis in spite of the fact that they are very informative. Analyzing solutions (8) and (10) we see that for the given circuit (Wo, C, L) velocity m is defined by relation A/m. To obtain a short time of the PFS current switching off ($\tau_{lo} \approx \frac{\ell}{v_m}$, see above) this relation should be increased but if we decrease only mass m then the CS energy losses will be increased for kinetic energy and that remained in the capacitor, and the energy of IS will be reduced. It is worth noting that for a sine IS current, velocity and a path covered by the shell are connected by relatively accurate expression(9). From (9) it follows that in going to the capacitive store with shorter rise time tm, the inductive store enables either velocity v_m to be increased at a fixed path x_m or x_m to be decreased at a specified v_m, as a result energy transfer from CS to IS will be improved. One should take this conclusion into account in the design of high-power facilities with an inductive energy store and CS must have a discharge circuit with minimum possible rise time.

4. Analysis of Pulsed Current Generators

More compact and cheap capacitive energy stores are usually built on the basis of capacitors connected in series - in parallel to provide necessary voltage Uo, capacitance C and energy $Wo=CU^2/2$. The third value characterizing discharge circuit of CS is inductance L which is defined by CS geometrical dimensions, type of capacitors (their own inductance) and by the topology of capacitors connection with a load.

Generally for the capacitor the following condition is met even in the mode of circuit short shorting:

$$\omega\tau<<1, \tag{4.1}$$

where $\omega = \frac{1}{\sqrt{LC}}$ is the frequency of natural oscillations of a capacitor circuit with the inductance of short circuit L and capacitance C; $\tau = l\sqrt{\varepsilon\varepsilon_0\mu_0}$ - is the time of electromagnetic TEM wave travel in a dielectric with permittivity ε along the foil of the capacitor sections (coats). This condition means that the mode of discharge is quasi-stationary and the capacitor may be taken as a lumped element of the circuit having inductance L, capacitance C and resistance R.

Capacitive energy stores are combined with a load by means of transmission lines that satisfy condition (4.1) and thus they are lumped C_{tl} and L_{tl}, but in IS powering we shall be interested only in L_{tl} or C_{tl} has effect only on the voltage overshoots that may occur in switching and give much trouble for the line insulation due to voltage excess.

As a rule, the stores with the energy > 100 kJ are built as single-type modules (cells) consisting of different capacitors or as a group of capacitors with common switch. Energy stored by an individual module is limited by the value that doesn't cause large damages in the break-down of one capacitor and in the discharge on it of all the module capacitors. Usually it is <10 kJ and it may be increased while using protection measures. In fast CS each capacitor is connected to the load with its discharger and transmission line in order to avoid break-downs in charging the module and to decrease the total inductance.

In reality, maximum operating voltage of devices for capacitor charging doesn't exceed 100 kW, so if the CS output voltage is needed to be higher than this value, Marx circuit of voltage multiplying is used. It enables to charge all capacitors in parallel and discharge them in series. To provide N-fold voltage multiplying one needs N switches. When Marx circuit with polar-different charging of adjacent capacitors is used, required number of switches is N/2, but

operating voltage of the discharger will be doubled. In a general sense, Marx generator may be taken as capacitor with C=Co/N and U=NUo.

The overall inductance of CS circuit is defined by:

$$L = \frac{L_g}{N_g} + \frac{L_{tl}}{N_{tl}} + L_{is}, \tag{4.2}$$

where Lg - module inductance; Ng - number of modules; Ltl - inductance of transmission line; Ntl - number of parallel lines; Lis - inductance of a vacuum energy store. Inductance of the module is defined by expression:

$$L_g = \left(\frac{L_c}{N_{c2}} + L_s + L_f \right) N_n, \tag{4.3}$$

where Lc - capacitor inductance; Nc2 - number of parallel- connected capacitors; Ls - inductance of the switch; Lf - inductance of a capacitor reverse conductor; Nn - number of generator Marx stages.

Such CS will have a rise time tmax defined by the following expression:

$$t_{max} = \frac{\pi}{2}\sqrt{L_\Sigma C_g}.$$

Assuming that we developed the generator with inductance Ltl+Lis<<L_Σ we can obtain minimum possible current rise time in a circuit which coincides with an individual capacitor characteristic $t_c = \frac{\pi}{2}\sqrt{L_c C_c}$. As a consequence we have to choose for CS capacitors with a maximum own frequency $f = \frac{2\pi}{\sqrt{LC}}$. At the same time, it is better to use capacitors with high volume density of the energy, that will result in decreasing CS dimensions and inductance of both modules and transmission line. The following capacitor features are very important for CS reliability in service:

low energy losses in the mode of discharging;

sufficient service life in the mode of multiple charges into the load;

high dynamic stability of internal connections and terminals of a capacitor;

design of terminals and the case that provides convenient low inductive connection with other elements of the store.

Standard value of the natural frequency of CS capacitors is in the range of 500-1000 kHz at specific energy density δ=100-500 kJ/m^3 (in actual designs δ=200 kJ/m^3). δ defines the volume of CS occupied by capacitors, and if a correction factor k=1.2 for high-voltage insulation and the volume of interconnections is inserted, then V_{cs}= 1.2 Wo/δ. As for CS with Wo=10 MJ its volume will be V_{cs}=60 m^3 (e.g. 3x3x7 m^3).

For the sake of convenience, modules of CS are located around circumference with the load in its center. In this case transmission lines from a load to the module may be made identical and all the modules will operate under the same time and current conditions. Then a geometry length of a transmission line l_{tl} will be effected by the module dimensions. Assuming that in section CS module will have dimensions axb (see Fig. .4.1), $r_{cs}=l_{tl}=\frac{V_{cs}}{2\pi ab}$.

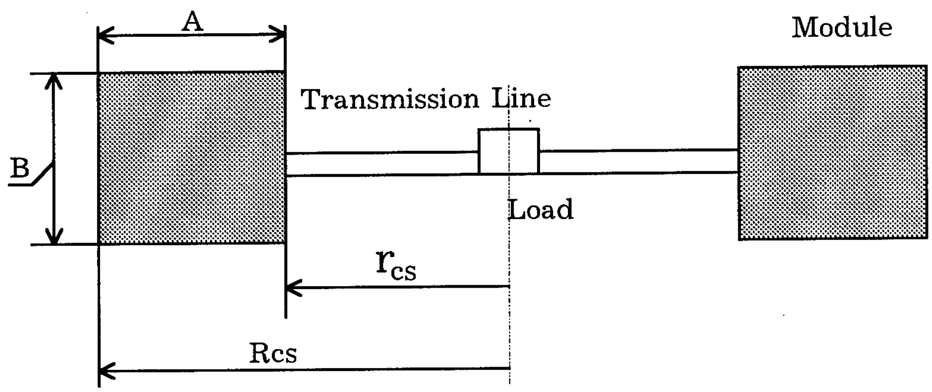

Fig. 4.1. Lay-out circuit of the capacitive energy store for a facility with PFS.

For example, with ab=1 m^2, r_{cs}=10m, at

(a=1)(b=4)=4m^2, inner radius r_{cs}=2.5 m and outer radius R_{cs}=3.5 m. These values testify to the fact that CS may be arranged as rather small- sized.

5. Choosing of the Facility Ideology

In order to reduce dimensions and to increase maximum current of a plasma-flow switch up to 25 MA we suppose to use structural circuit of a facility with a capacitive store consisting of 20 separate modules having energy storage 500 kJ each. The energy from every module, made of 4 Marx generators, through a separating oil-vacuum insulator is transferred along 20 magneto-insulated vacuum transmission lines which by means of convolute are connected with coaxial electrodes of a plasma-flow switch. To increase the energizing power of PFS and to reduce the time of powering we try to obtain minimum inductance of a circuit and want the CS inductance to be the largest part of a discharge circuit inductance, e.g. 75% of total inductance. On PFS operation a voltage pulse with duration = 100 ns and amplitude >2 MV appears in the load. The voltage will distribute among the elements of the circuit proportionally to the inductance of a coaxial chamber sections, MITL,

inductance of the module capacitors and connecting buses of the modules. We believe that generator Marx is able to bear the overvoltage of an inductive nature 1.5-2 times than its output voltage, in case the conditions for electric strength between high-voltage electrodes are fulfilled. Really, if a voltage pulse in the module is considered at the instant of rupture, it is defined by expression $U=LI/t_{im}$.

This voltage is applied to the inductance of a capacitor, discharger, and connecting bars. In actual designs of Marx generators inductance of capacitors accounts for 20-50% of total inductance. With such a relation between capacitors inductance and overall inductance of the generator it is possible without sacrifice of capacitors insulation to apply voltage to the module at the instant of rupture that is 2-5 times higher than output voltage of the module in a shock, as it is distributed along a discharge circuit proportionally to the inductance of sections. But insulation between current-carrying parts of the module is to be calculated for a value of overvoltage.

Consideration of the above peculiarities of the Marx circuit allows to use Marx generator itself as a magnetic energy storage, and MITL is mainly used only to transfer magnetic energy from Marx generator into a load. In this case conditions of MITL operation became close to evaluated characteristics of MITL with a pulse duration <100 ns [21, 22]. Actually in PFS powering from CS, the voltage at a vacuum insulator and at the input to MITL will be 20% of the output voltage of Marx generator (U_o=1080 kV) since CS inductance accounts for 80% of the total inductance.

Magnetic field in each MITL is 2.5 T and it is comparable with a magnetic field value for PES with a microsecond powering time [15]. In this situation facility may be used in three versions:

<u>as a driver with a plasma-flow switch for imploding plasma shell;</u>

<u>as a driver for plasma toroid acceleration;</u>

<u>as a set of 20 independent drivers for high-current electron diodes</u> (U>2 MV, I=0.5-1 MA) to generate bremsstrahlung X-ray radiation of a total power $5 10^{13}$ W.

Such ample capabilities of the facility may be obtained by replacing only small parts of a load without touching CS and MITL. Possibility to use for MITL current commutation 20 separate plasma opening switches for operation on to a common plasma imploding shell or onto 20 individual electron diodes to generate a pulse of bremsstrahlung will be realized if the scatter a separate PES operation (the first - the last) will be smaller 20 ns. Then the duration of the total current rise time will be <100 ns. Analogous accuracy of PES operation

has been reached in the development of a switch for the facility DECADE [24] and this allows us to have an optimistic view of realization of the 3-d version of the facility application.

In summary we may determine basic versions of the facility and its main parameters:

1. Number of a CS modules, Nm	20
2. Total store energy, Wo	10 MJ
3. Peak current, I	25 MA
4. Output voltage of CS, U	1 MV
5. Power of CS, Po	510^{13} W
6. Capacitance of CS, C	20 μF
7. Inductance of IS, Lis	25 nH
8. Duration of IS powering, tp	1 μs
9. Number of MITL, Nt1	20
11. Number of vacuum diodes, Ndiode	20
12. Time of PFS current switching, τfs	100 ns
13. Time of PES current switching, τss	100 ns
14. Generated voltage, Ulo	2-3 MV
15. Power of a switch, Plo	0.510^{14} W

5.1. Choice of the capacitive store parameters

In item 2 we examined energy features of IS current switching by an opening switch onto imploding shell. Actual shells have an inductance increment δL_{lo}=20-30 nH. From this it follows that inductance of the IS circuit $L\Sigma=L_g+L_{tl}+L_{is}$- must be less than δL_{lo}. In actual design it will be defined by a large number of factors. It is possible that this condition will not be the governing factor, since to transfer current from a large number of modules through transmission lines of a large length, the voltage of CS should be increased that causes the increasing of CS inductance, otherwise (see item 2) the CS current derivative will drop $\left.\frac{dI}{dt}\right|_{max} = \frac{U}{L\Sigma}$.

We beforehand studied the versions of a CS design, transmission line and coaxial chamber of a plasma-flow switch for different output voltages of CS: 360 kV, 500 kV, 720 kV, 1080 kV and 2 MV. For the first three versions it turned out that in terms of design it is impossible to obtain a circuit inductance providing about a microsecond current rise time, it was 1.5-2 μs at best. This is associated to the fact that with equal energy storage the capacitance of CS is in

inverse proportion to the square of voltage, and the circuit inductance is defined by geometry dimensions which in practice can't be changed and in all cases it is about the same. The rest of the variants are easier in design realization relative to inductance and current rise time duration but at 2 MV voltage of CS, the total inductance of the circuit is beginning to increase due to the increasing CS inductance and this deteriorates performance of the facility onto imploding shell. When it is considered that on operation plasma switch further increases the voltage as compared with an initial one by a factor of 2-5, this facility can operate only onto a vacuum or ion diode limiting the variety of applications.

Thus, we choose inductance of IS $L\Sigma$=25 nH. Without active losses (R=0) we shall obtain maximum IS current $I_m = \sqrt{\frac{2W_0}{L}}$ .. and for Wo=10 MJ Im=28 MA. With an output voltage of the Marx generator U=1 MV we have $C = \frac{2W_0}{U^2} = 20.10^{-6}$ F.

Now our task is to design a facility with the following parameters:

$L\Sigma$=25 nH;

$C_{cs}=20.10^{-6}$ F;

Uo=1 MV.

As Uo > 100 kV then Marx circuit with Ncl > 5 stages is to be used . A number of generators will be defined by a capacitance (energy yield) of one capacitor. Let us take a capacitor used in ACE-4 [12]: C=1,5 μF with a polar-different charging +/- 90 kV, then one Marx generator made of 6 capacitors connected according to the Marx circuit will store the energy W_1=125 kJ. The total number of these generators in CS will be $N_r=W_0/W_1$=80 pieces. Four Marx generators work in parallel into one magneto-isolated transmission line.

5.2. Calculation of characteristics for the Marx generator

Capacitive pot of every Marx generator stage consists of a capacitor with 1,5 μF. Each has the inductance of 28 nH, charging voltage is +/- 90 kV. Capacitors are connected with the generator circuit in parallel through a discharger. Inductance of each pot is 56 nH, capacitance - 1.5 μF, output voltage - 180 kV. Six-stage generator "in shock" has capacitance Cg=0.25 μF, output voltage Ug=1.08 MV, energy storage 125 kJ in charging +/-80 kV. The generator design is located in a tank with transformer oil. Overall inductance of the generator circuit involves the inductance of capacitors, discharges and conductors bars.

1. Inductance of six capacitor stages is Lc=56 x 6=336 nH.

2. Inductance of discharges is determined as inductance of a direct turn by the following formula:

$$L_s = \mu_0 k_r \frac{S}{h},$$

here Kr(a=b, h/2/a=1.3)=0.75; h=40 cm; a=b=15 cm. Then the inductance of on discharger will be Ls=53 nH, and that of all six will be Ls=53x6=318 nH;

3. Inductance of the generator bars may be estimated by the formula:

$$Lf = \mu_0 \frac{\delta}{h} k\left(\frac{\delta}{h}\right) lf,$$

where δ- is the gap length between buses, h- is the width of the bus, 1f- is the length of the bus, $k=k\left(\frac{\delta}{h}\right)$- is a coefficient.

The gap between the buses is taken equal to 12 cm. With the electric strength of a transformer oil of 200 kV/cm, breakdown voltage between bars is 2.4 MV. The width of a bus is taken equal to the width of a capacitive bath H=40 cm. The length of the buses consists of the heights of 6 capacitors and the length of a gap between them. With the gap d=4 cm, the length of buses will be Lb=30x6+4x5=200 cm and their inductance Lb=560 nH, k=0.75.

The overall generator inductance involves the inductance of capacitor, discharges and conductors and it is Lr=Lc+Ls+Lf=1.2 μH. This value of the Marx generator inductance results in total inductance of 80 generators equal to 15 nH. The design and electrical circuit of Marx generator are shown in Fig. 5.1 and Fig. 5.2.

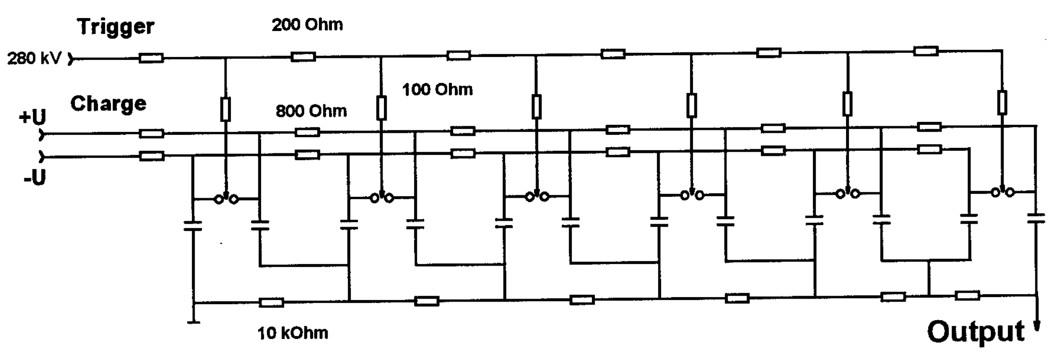

Fig. 5.1. Electrical circuit of Marx generator .

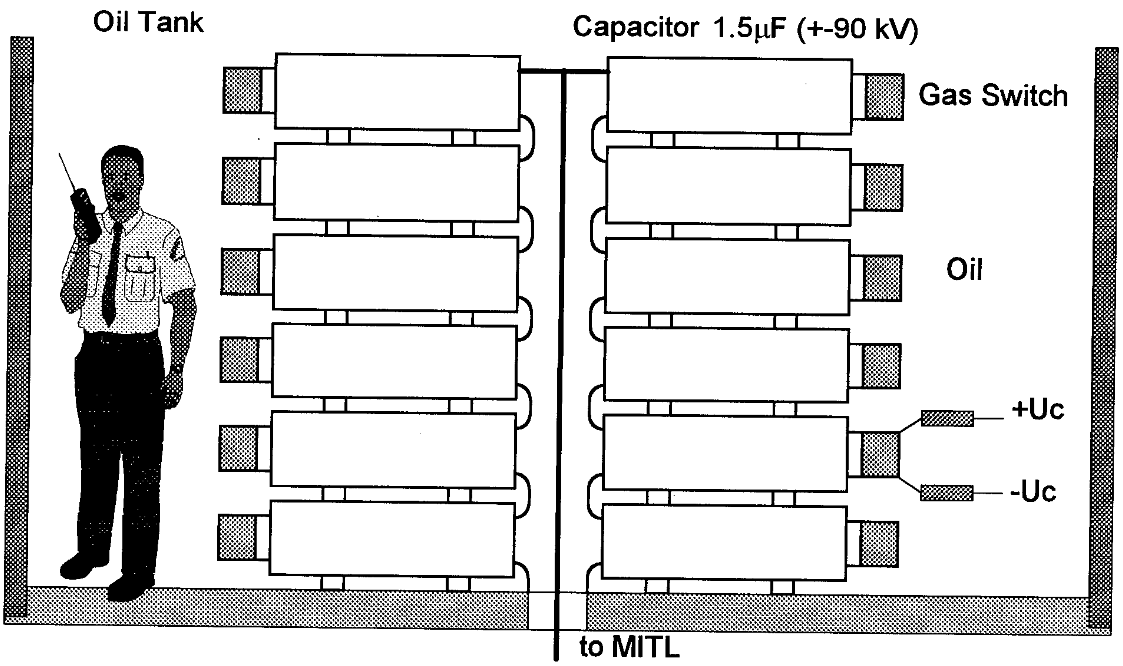

Fig. 5.2. A version of the generator Marx arrangement at one level in CS.

5.3. Arrangement of the facility capacitive store

The most sound design of CS modules is their arrangement at equal and minimum distance from the load defined by cross section of an individual generator. However, in this case the modules are to be arranged on a sphere surface. It goes without saying that in practice this design will be very complicated in production and service. Therefore, generators are usually located around the circumference in one or several raw about the load. In our case, the minimum size of the Marx generator equals the minimum size of the capacitor. We select capacitors used in ACE4 (1.5 μF, +/- 90 kV) [25]. Their dimensions are 0.8x0.4x0.3 m. We choose a gap along the circumference between adjacent generators for maximum voltage U=2 MV, for transformer oil it is 10 cm. Thus, one generator occupies a length of 0.5 m around the circumference. Hence, for the generators arrangement shown in Fig. 5.3. the inner circumference radius of the generators arrangement for N=20 will be ri=3.2 m. Generator length to a common high-voltage electrode is 1 m, therefore the outer radius of the store will be ro=4.2 m.

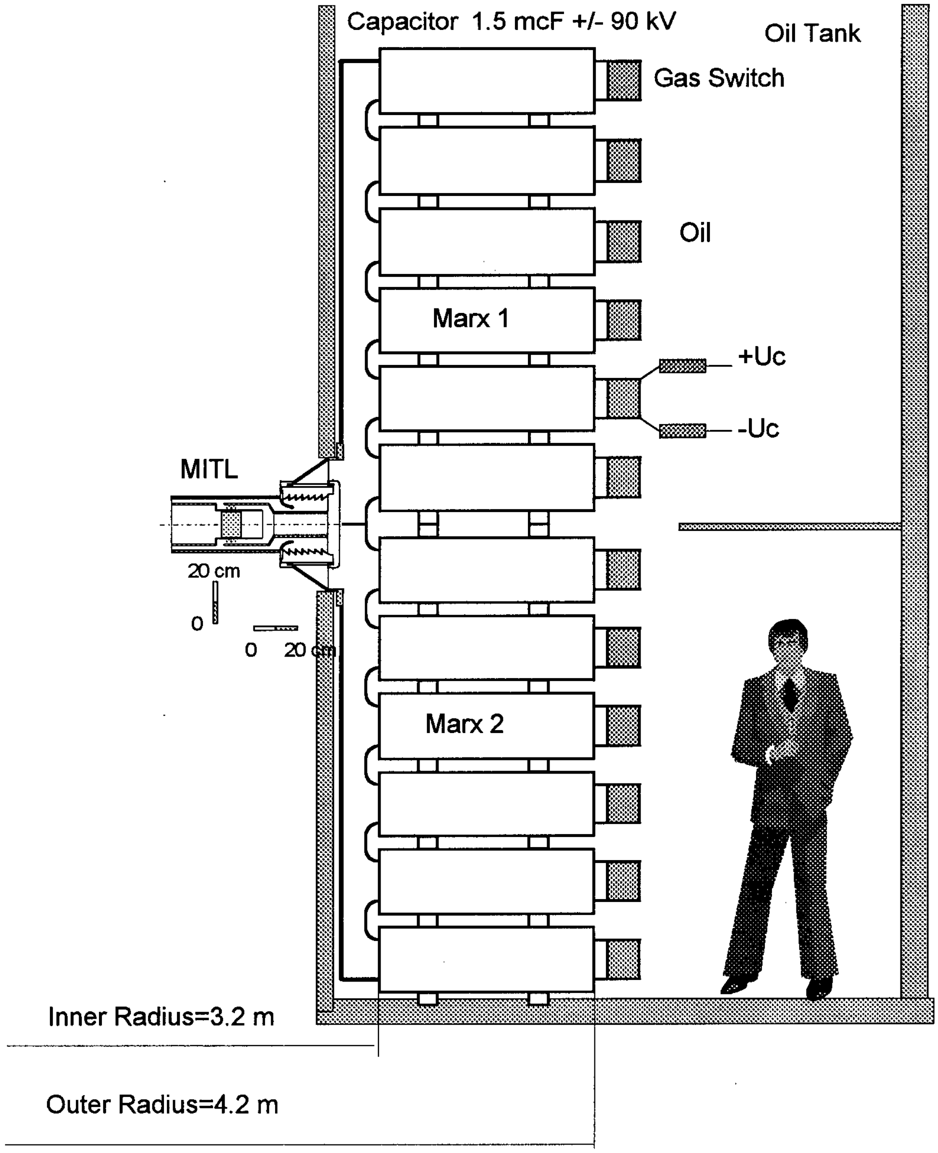

Fig. 5.3. Version of a CS module design with Marx generators arranged one above the other.

Insulation of high-voltage parts of CS is effected by transformer oil, therefore it is necessary to choose a method of filling. In practice these are two approaches differing in a production technologies, service and total quantity of transformer oil. Designers of the Physical International Company (USA) usually use metal tanks for every CS module [24]. In this case the volume of the oil required decreases, but maintenance of elements and units of CS becomes labour consuming. Sandia National Laboratories (USA) used widely different approach in the design of such facilities as PBFAII, SATURN, PROTO -II [22].

In these facilities the capacitive store was located in a common ring tank witch is easily accessible for the personnel for repair and inspection of the CS elements. But then, the volume of oil is increased as it is necessary to make around CS the passages for the staff.

For our facility we have chosen a version with a common tank as easy-to- use and to repair CS. Four modules of the Marx generator operate in parallel in one transmission line. In the first module involving 4 generators Marx 500 kJ of energy is stored. It will provide an input current >1 MA in 1 μs at an output voltage of an no-load 1080 kV. Dischargers must ensure current >250 kA and irregularity of operation (the first-the last) less than 10 ns. For this purpose were used dischargers controlled by means of the field distortion by the 4-stage driving generator Marx with an output voltage 208 kV, energy storage 1 kJ and pulse duration <50 ns.

CS reliability is an important problem which is aggravated by the capacitors operation with currents close to the currents of short-circuit. To increase the service life it is necessary to insert into the Marx generator circuit the damping resistance which, in spite of the fact that it restricts the current, will reduce the level of changing the poles of the voltage in capacitors. A value of the damping voltage may be selected from the compromise between the reliability and maximum current. These resistors will also decrease maximum current in case of catastrophic breakdown of one of the generator modules on which the rest of the generator modules will discharge. The influence of the remainder of CS modules will be distinctly weaker since they are separated one from the other through the inductance of MITL. MITL inductance is=100 nH so the current in the failed MITL line will be I_{tl}<2 MA at the switch voltage 2 MV and pulse duration 100 ns.

This is a more complicated problem to ensure the lack of damages in CS or vacuum insulators of MITL in the facility operation into a plasma opening switch and a plasma load, if PES plasma and the load plasma are generated pulse wise in one or another way in case of the systems failure. Then MITL and the central electrode of the coaxial chamber will work in the mode of an electron diode, and the voltage at the electrodes may reach the voltage of the modules no-load 1 MV. If on the insulator surface of one of 20 MITLs breakdown occurs, all of the modules will start discharging onto the punctured insulator and the current may increase an allowable value and this insulator will be destroyed.

This problem can be solved by using an additional plasma switch located at the input of the MITL central conductor, its circuit is shown in fig. 5.4.

Application of this switch with a breaking current 1.5 times higher than the module current, will make it possible to switch the failed insulator off the MITL as the current drastically increases.

This switch works in the following manner: a plasma layer 3 with a mass m is produced by the plasma gun between electrodes 1 and 2. This plasma will short-circuit electrodes 1 and 2 and through the plasma a current of CS module will flow into MITL and then into the load.

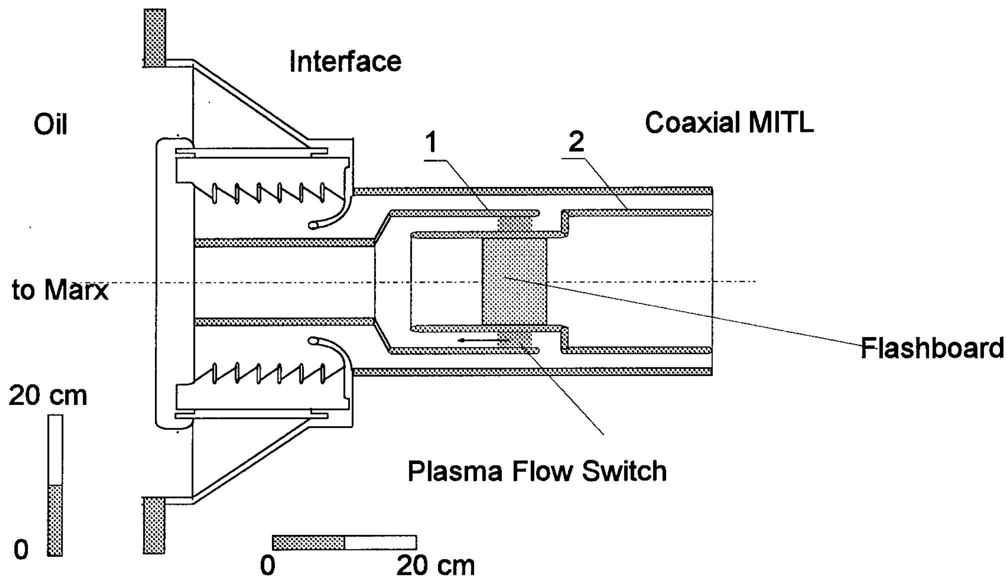

Fig. 5.4 Plasma switch for MITL current excess protection while the breakdown in the insulator.

Under operating conditions, such plasma mass is chosen, that the ring plasma shell accelerated by magnetic field doesn't reach the end of electrode 2 for the time of the vacuum chamber powering. If in one of CS a failure takes place, the value of magnetic field in MITL will increase and the shell will break away from the end of electrode 2, and the failed module will be disconnected. Therefore a supplementary plasma switch may be used to protect the facility from damage.

5.4. Design of a transmission line.

A transmission line with the operating voltage >2 MV must possess minimum inductance $L_{TL} << L\Sigma$. The inductive store has a vacuum coaxial chamber so, it is better to use this dielectric in transmission line too, moreover,

electric strength of the vacuum gap is much higher than that of another dielectric. Separating insulator may be installed at the input of a transmission line, and thus to remove the insulator surface far from the PFS plasma and to decrease its radiation by ultraviolet which reduces electric strength of the insulator vacuum surface. A sample structure of the insulator is shown in Fig. 5.5.

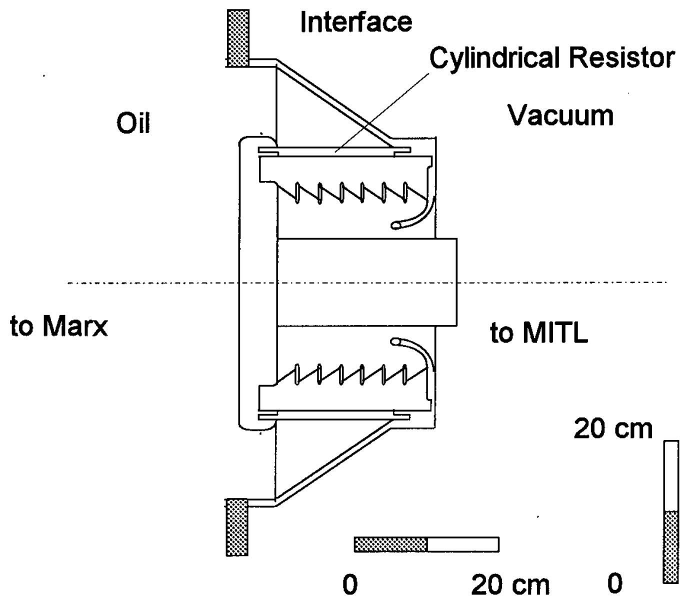

Fig. 5.5. Vacuum insulator

Vacuum insulator of each module is made of a set from 7 acrylic rings with an outer diameter 40 cm and gradient rings. The total insulator length is 20 cm. The internal surface of the rings is inclined at the angle 45° in order to obtain maximum electric strength. Electric strength of the insulator is determined from the formula [24]:

$$(U / d)t^{0.17}A^{0.1} \leq 175 kV / cm,$$

where t is duration in μs, A - is the surface area in cm^2. With the pulse of MITL powering voltage t=0.7 μs, and the pulse under switching t=0.3 μs, the insulator surface area is 2400 cm^2. For the powering pulse electric strength of the insulator is 100 kV/cm and for the switching pulse it is 185 kV/cm. If in the criteria the area of all 20 insulators are taken into account these values will be 75 and 140 kV/cm respectively. To equalize the distribution of an electric intensity along the insulator length a cylindrical resistor is placed on the external surface which is analogous to that used in work [30]. Inductance of the vacuum insulator is 100 nH.

Vacuum transmission lines are widely used in powerful high-voltage accelerators of electron and ions [20, 22]. At the facility PBFA-I operating electric strength of vacuum gaps reached 1.6 MV/cm, and on facility SATURN it was 1.9 MV/cm with the duration of a voltage pulse 40 ns FWHM. In [38] experimental investigation of the 2 meter length vacuum line with the electric intensity up to 200 MV/cm and maximum inductance of a magnetic field up to 3 T is presented. Such large values of an electric field intensity in vacuum gap are explained by full magnetization of electrons in the gap by the magnetic field of transmission line current. Larmor radius of an electron becomes smaller than an interelectrode gap, and electrons escaping from the cathode don't reach the opposite electrode (anode) of the TL [21]. Then with I_{tl}=3 m and operating intensity at the instant of operation of either CS (Ecs=0.1 MV/m) or PFS (Epfs=100 MV/m), we use the gap between an electrode of a coaxial TL equal to r1-r2=2 cm and estimate an inductance of one TL as $L_{tl1} = \frac{\mu_0 \ell_{tl}}{2\pi} \ln \frac{r_1}{r_2}$,, where r1=12 cm, r2=10 cm are outer and inner radii of TL coaxial. Then Ltl=120 nH. Overall inductance of all 20 TLs will be $L_{tl} = \frac{L_{tl1}}{N_{tl}} = 6$ nH.

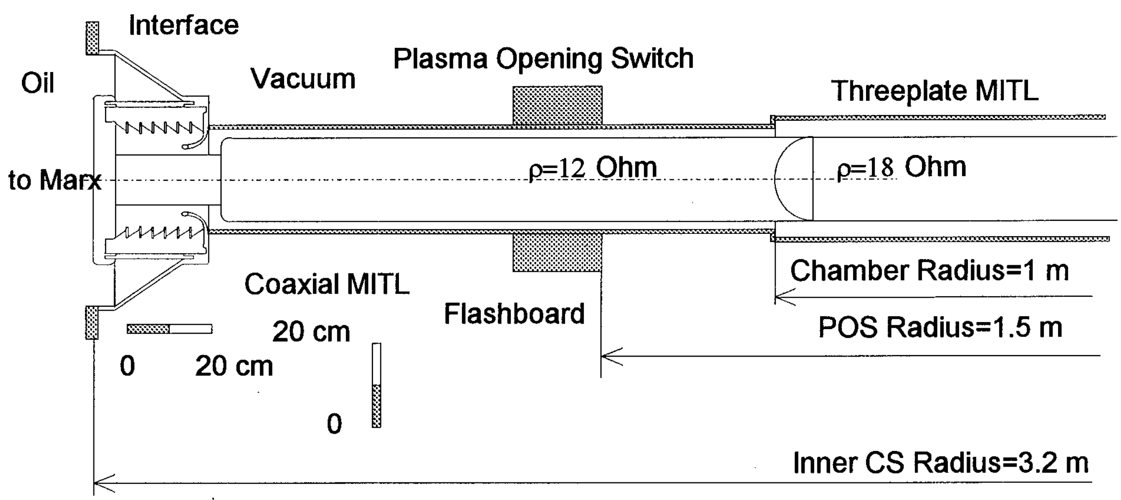

Fig. 5.6. Configuration of a magneto-insulated transmission line

MITL design is given in fig. 5.6. From the vacuum insulator of CS module to the working chamber it is made in a form of coaxial with an inner diameter 20 cm, a gap of 2 cm and 2 m length. In a volume of the working chamber the coaxial line changes to a threeplate load with 2 cm gap. Its central electrode is of 20 cm width and 1 cm thick. Along this line the current is delivered to a coaxial gun of 20 cm in radius. Wave impedance of a coaxial line is 12 Ohm and

that of threeplate line is 18 Ohm. Reduced to a separate line the switch resistance is 2 Ohm and with such relation between it and line impedance the gap will have good magnetic insulation [35].

MITL offers two operating conditions:

powering of a plasma switch;

switching into a load.

While powering, the voltage in the line electrodes is defined by a relation between inductances of the load and a plasma charge with the inductance of a capacitive stores. Electric field intensity at the electrodes will not exceed 100 kV/cm and this voltage pulse will have duration 500 ns FWHM (voltage pulse of cos(ωt) form). This value is one-third as many as the threshold intensity of an electric field at the MITL cathode, wherein cathode plasma is produced closing the electrodes. Thus, electron flows generated while powering from cathode to anode will be insignificant and will quickly cease as soon as a specific value is reached, i.e. with the occurrence magnetic insulation [36].

In the switching conditions the major voltage pulse with an amplitude of 2-3 MV, duration <100 ns generated on operation of PFS, will be applied to MITL on the load side, and the field intensity between the electrodes will be 100 MV/m. At this point magnetic field in MITL will be maximum (B=2.5 T). At so high intensity of an electric field, the cathode plasma will be necessarily produced and it will short-circuit the gap anode-cathode at a rate of 2-6 cm/μs. Magnet field in MITL will restrict the velocity of plasma propagation [36], so there is a hope for the low limit of plasma velocity. This corresponds to the time of MITL closing from 0.3 μs to 0.5 μs. MITL will be able to transfer energy from CS inductance during 0.3-0.5 μs, that exceeds the time of energy output from CS inductance into the load which is less than 0.3 μs.

A fraction of the electrons current in the vacuum gap may be estimated from simple assumptions. With initiation of the field E=100 MV/m at the cathodes surface a charge occurs with the density $\sigma = \varepsilon_0 E$, where $\varepsilon_0 = 8.85 \times 10^{-12}\,\mathrm{F/m}$ and these electrons will drift in crossed CS fields towards the load. The movement of a volume charge is characterized by the drift velocity $V_d = \frac{E}{B}$ and maximum distance from the cathode $\rho_e = \frac{m_e E}{eB^2}$ (ρ=0.1 mm). Then the current of electrons in vacuum is $I_v = \frac{2\pi\varepsilon_0 r E^2}{B}$, where r - is the radius of cathode. For our parameters (r=0.1 m, B=2.5 T and E=100 MV/m) I_V=22 kA. It is worth nothing, that the field of 2.5 T is not sufficient for magnetic insulation to be observed and for ions $\rho_i = \frac{m_i E}{eZB^2}$, where Z is the ion

charge. So, even for the hydrogen ions ρ=16.6 cm that exceeds the gap between the electrodes, therefore between the MILT electrodes an ion current will flow in case of the anode plasma occurrence.

5.5. Working chamber design of a plasma-flow discharge.

As we have already mentioned, PFS is a coaxial plasma gun that accelerates a ring plasma shell towards the load. Overall dimensions of coaxial electrodes were chosen on the basis of experimental data obtained with the facility SHIVA STAR [17]. Maximum intensity of the magnetic field in "Quick fire" experiments was $H \approx 2 \cdot 10^7$ A/m (b=25 T). On retention of this parameter, at peak current of IS equal to 25 MA, diameter of the inner electrode must be Ø =40 cm, gap between the electrodes d=2.5 cm. In this case PFS inductance per unit length is A=0.25 nH/cm. The path length of a plasma shell acceleration is s_0=10 cm. At this distance from the place of a wire array and a barrier foil the ledge is on the inner electrode, plasma shell breaks away from this ledge. Flow switch plasma is thrown out of the chamber volume through the holes between the vanes connecting the load with outer electrode. Construction of the PFS central part is shown in Fig. 5.7.

Three-plate MITLs are connected with the coaxial PFS electrodes by post-hole convolute. Vacuum gaps of the convolute are chosen equal to 2 cm, the rods thickness - 1 cm, the width - 3 cm. Inductance of the convolute of 20 rods is estimated to be equal L=1 nH.

The load with 10 cm outer diameter and the length of 4 cm is connected to the PFS electrodes by means of a transmission line with the inductance L=5.5 nH. Vacuum insulation between coaxial electrodes of the chamber and the transmission line to the load is provided by 2 cm gap and by high value of magnetic field. With the current in the switch 25 MA the field in a coaxial part is 25 T and in a transmission line to the load it may by even higher (up to 0.1 kT). Magnetic intensity in the chamber reaches, the maximum value in a coaxial part of the chamber $H \approx 2 \cdot 10^7$ A/m, B=25 T, in rods of the convolute the field reaches $H \approx 1.5 \cdot 10^7$ A/m, in a three-plate MITL $H \approx 3 \cdot 10^6$ A/m, in the coaxial MITL $H \approx 2 \cdot 10^6$ A/m and at the inner electrode of the vacuum insulator $H \approx 5 \cdot 10^6$ A/m.

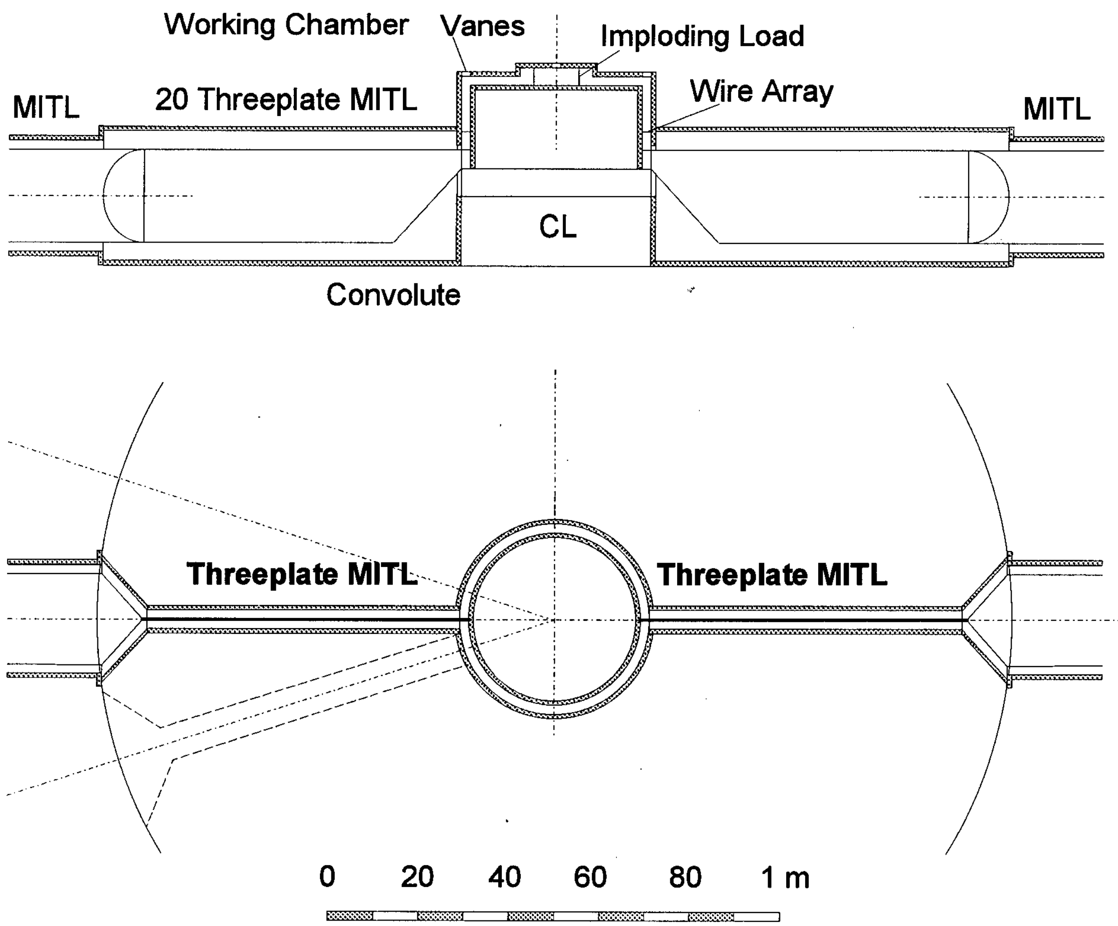

Fig. 5.7. Coaxial part of the vacuum chamber.

6. Characteristics of facility with a plasma-flow discharge.

In order to determine the basic features of the facility for the parameters chosen, we have made calculations using the program discussed in section 3.1. Calculation curves are given in Fig. 6.1. The system of equations (1)-(5) was solved for the circuit parameters A=dL/dx=0.25 nH/cm, mass of the plasma shell m=12.5 mg, acceleration distance d0=10 cm, inductance of the circuit Lo=25 nH, CS capacitance C=20 μF, resistance of the circuit R=1.5 mOhm and voltage of CS U=1 MV. In a geometry of the plasma-flow switch the condition was inserted that when the acceleration path is down, the plasma shell leaves the volume of the chamber through the holes among the vanes by which coaxial electrodes of the chamber are short-circuited.

Our estimate is that at the instant of the plasma escape, 8.72 MJ will transfer in magnetic energy of the circuit, 0.67 MJ will contribute to the plasma kinetic energy and the rest of the energy will remain in capacitors of CS and will be absorbed in ohmic resistance of the circuit. At the point t=1.01 μs the circuit current will reach the value Idis=24.9 MA and the plasma velocity v=32.7 cm/μs.

Higher velocities of plasma can be obtained if still smaller plasma mass is taken, but then magnetic energy will be decreased. Special attention must be taken to the current increase in the circuit after the shell's escape out of chamber, it is explained by the fact that to a moving shell the voltage **AvI** is applied which holds a fraction of voltage in CS capacitor and after the ejection of the shell it is beginning to increase current in the circuit. Therefore, the voltage at the capacitor, in breaking a current circuit by a switch, will be added to the voltage of a circuit breaker, increasing it.

Calculations of the facility parameters showed that the powering current of a plasma-flow switch about 25 MA may be obtained in ≈1 μs. In this case only the power of an inductive store powering is about 8 10^{12} W.

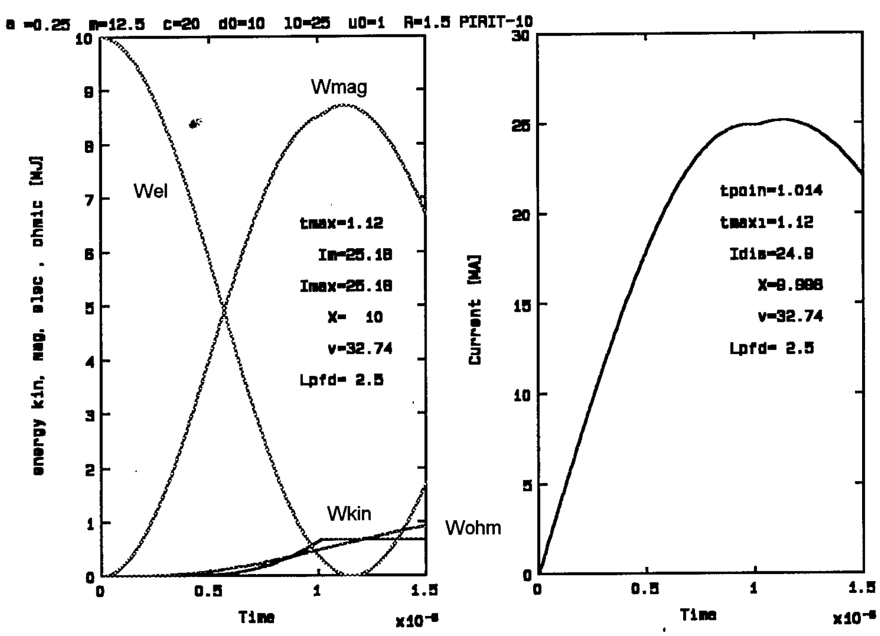

Fig. 6.1. Calculated features of a plasma-flow switch powering

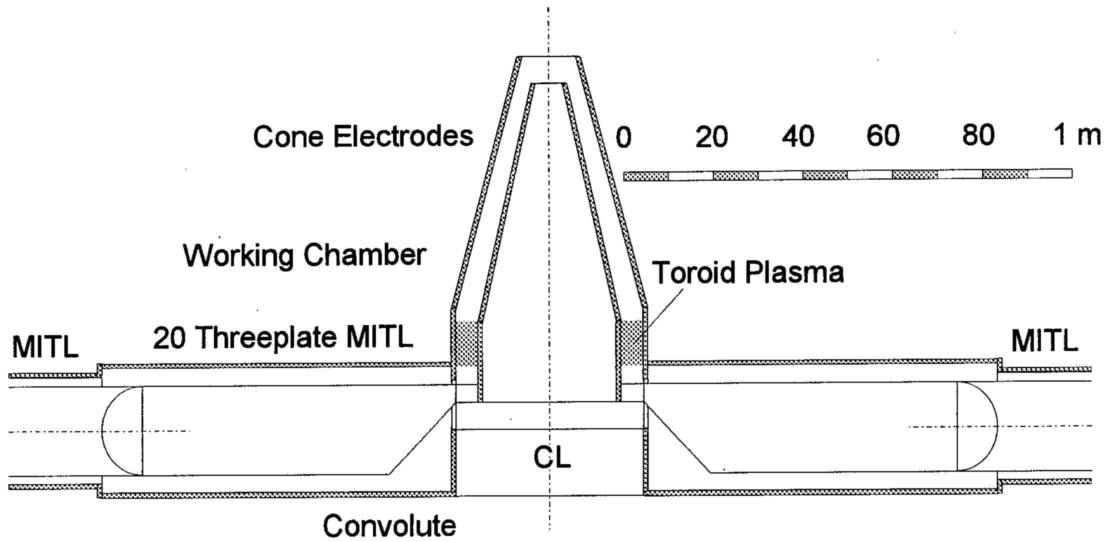

Fig. 7.1 Experimental working chamber for acceleration of plasma toroid.

7. Characteristics of facility in plasma toroids acceleration.

In order to use the facility in experiments on acceleration of stable toroidal plasmoids with the frozen in magnetic field, calculations are given in the geometry shown in Fig. 7.1. Acceleration distance was 70 cm, a gap between conical electrodes - 5 cm, initial radius of the inner electrode - 17 cm angle of the cone convergence - 12.75°. In Fig. 7.2 one can see dependencies of kinetic, magnetic energy, current in the circuit, plasma velocity and the plasma traveled distance for a plasma mass m=6 mg.

Kinetic energy of toroid as it leaves conical electrodes is W_{kin}=6.17 MJ with velocity v=157 cm/μs, and the magnetic field energy W_{mag}=2.9 MJ. At that point inductance of the circuit increases by 77.5 nH. In this case kinetic energy of plasma ions is reached W_i=12.8 keV/nucleon and if this energy is thermalized, the temperature of plasma can reach 10 keV and more if a matter with a large ion mass is used.

With the chosen geometry of electrodes the value of the plasma kinetic energy practically doesn't depend on plasma mass in the range of 6-125 mg and is about 6.25 MJ. Changing the mass results in different plasma velocity at the output from the conical acceleration track. This result is probably associated with the simplicity of the model used in calculations, but this is an indisputable fact, that using more powerful driver for toroid acceleration it is possible to obtain higher plasma velocity.

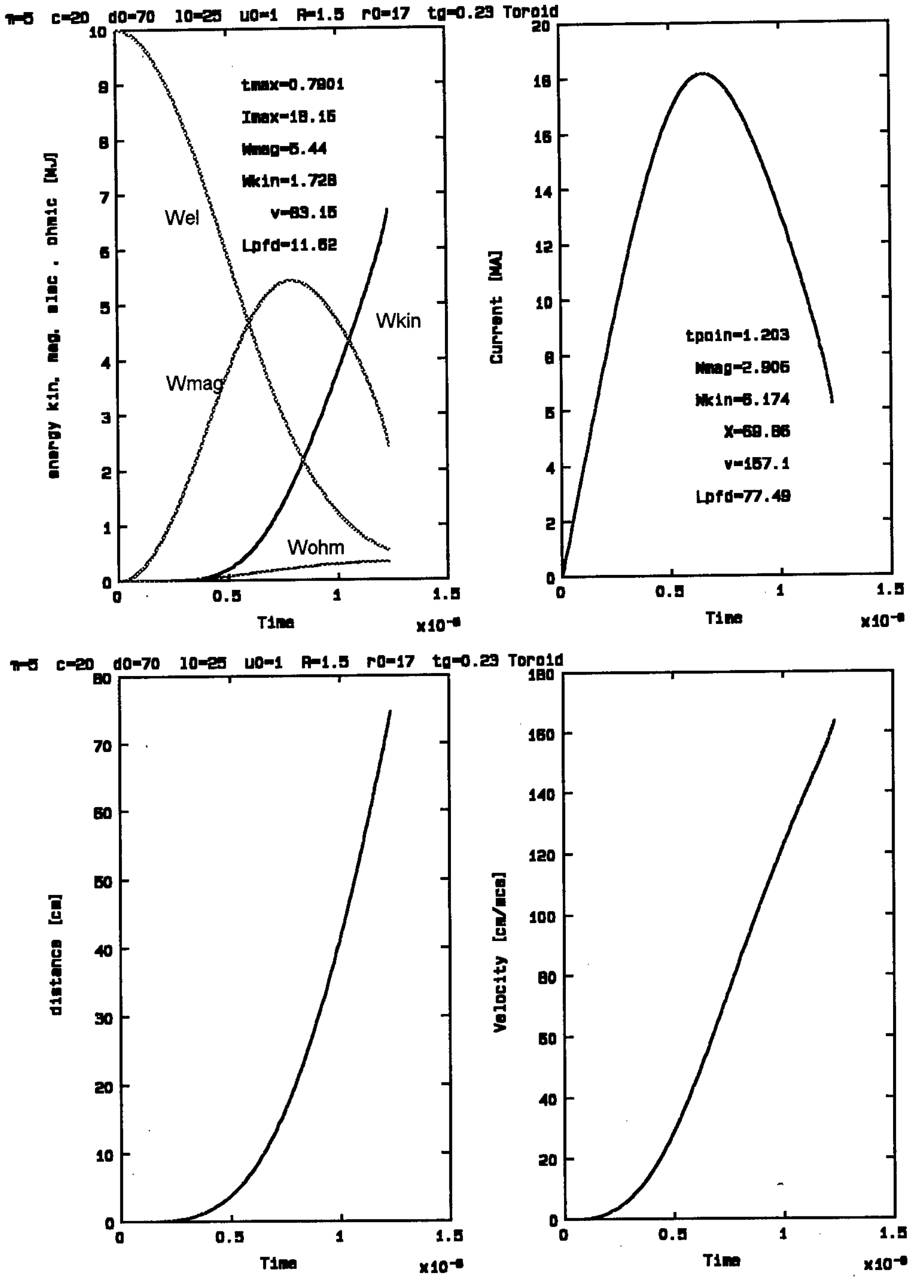

Fig. 7.2 Basic characteristics of plasma toroid acceleration with m=610^{-3}g.

8. Characteristics of a module with a plasma-erosive switch.

Constructive circuit of the facility permits the use of plasma-erosive switches for a current pulse forming of an isolated module. In particular, it is possible that as a load of every PES its independent vacuum diode will be used.

For numerical simulation of an opening process of the module current circuit 0-dimensional program has been used which calculates parameters of an

electric circuit as well as the movement and breakage of the switch plasma layer.

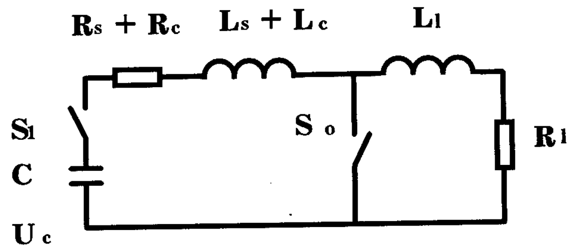

Fig. 8.1. Equivalent network of a discharge circuit.

Electrical circuit of Fig. 8.1. is described by a set of differential equations:

$$\frac{dUc}{dt} = -\frac{\Phi s}{C(Ls + Lc)};$$

$$\frac{d\Phi s}{dt} = Uc - Usw - \frac{(Rs + Rc)\Phi s}{Lc + Ls};$$

$$\frac{d\Phi l}{dt} = Usw - \frac{Rl\Phi l}{Ll};$$

Here U_c, U_{sw} - is the voltage at the capacitive store and the voltage at the plasma-erosive switch, Φ_s, Φ_l - is the magnetic flux in the circuits of the store and the load, R_s, R_c, R_l - is the resistance of an inductive store, capacitive store and the load. L_s, L_c, L_l - is the inductance of the inductive store, the of capacitive store and the load. This system should be complemented by the law the store inductance and load change and by the low of the voltage change at switch U_{sw}.

Increasing of the store inductance is determined by the motion of the switch plasma under the action of the pressure of the intrinsic magnetic field. To determine a voltage at the plasma-erosive switch one should find the movement of a double boundary layer as a result of plasma erosion by the current and the action of the magnetic field pressure. In the adjustment of the program, the results obtained with the experimental facilities "PIRIT" [15] were taken as the basis results.

Good agreement is observed between calculated and experimental results while taking into account a double layer motion due to the plasma erosion by the current, and if a magnetic field pressure is accounted for. Consideration of an electron component magnetic self-insulation causes increased values of voltage on the breakage, that probably may be attributed to the lack of self-insulation in experimental facilities or insufficiently precise description of the

self-insulation process in the program. Notice that in analogous calculations made in Japan the process of self-insulation was not taken into account either.

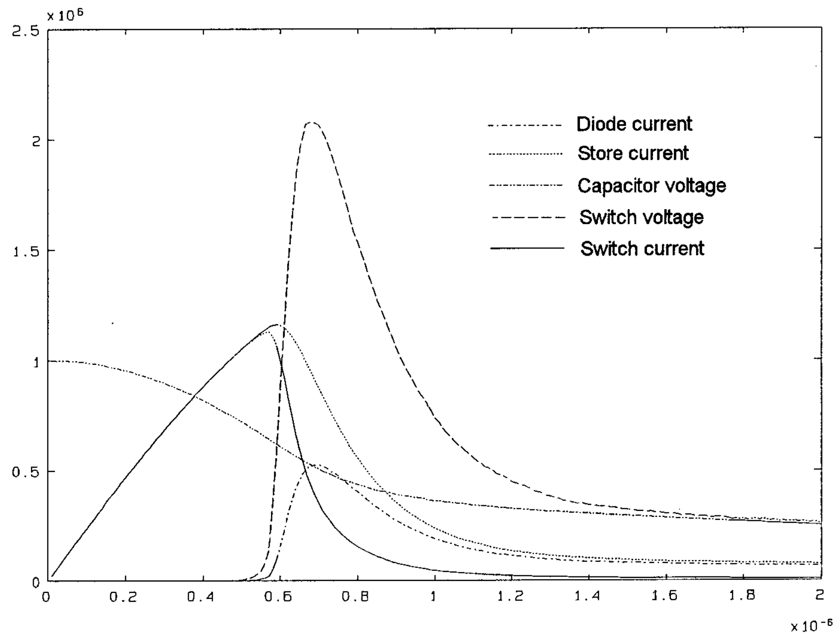

Fig. 8.2. Results of PES calculation when operating to a vacuum diode.

For calculation the following data may be taken as initial ones: module capacitance - 1 μF, inductance of a capacitive store - 0.3 μH, critical current of the switch - 1 MA, inductance of the load - 50 nH, diode resistance - 4 Ohm. Plasma of PES is ejected into a 3 cm gap of the coaxial with an outer diameter of 25 cm.

Main current and voltage dependencies are shown in Fig. 8.2. Plasma-erosive switch starts breaking at the instant of 0.7 μs, when the current of the store exceeds the critical current and reaches 1.1 MA. And in this case the voltage at 4 Ohm diode is more than 2 MV, i.e. voltage multiplication factor is 2. Under this operating conditions the diode current is 500 kA. Peak power at the diode is 1 TW, overall energy - 200 kJ and efficiency - 60%.

Should all the modules come into action simultaneously with scattering less then 20 ns, the total current of 20 modules will be 10 MA and an electron beam energy will be 4 MJ.

Conclusion.

A conceptual design of 10 MJ, 10 TW stationary facility for plasma-flow discharge (PFD) experiments with currents up to 25 MA is presented in this work. To solve the problem in hand we carried out analysis of available facilities with the capacitive energy stores and made calculations on a plasma-flow discharge powering in the mode of the current switching and plasma toroid. The emphasis in the project is on the reduction of the PFS powering duration that permits to increase the facility power and the energy of toroid. For this purpose, precautions have been taken to reduce inductance of a discharge circuit, and the high voltage of a capacitive store (1 MV) has been chosen.

10 MJ facility consists of 80 six-stage generators Marx with a voltage in a shock up to 1 MV connected in parallel to 20 modules with an overall capacitance 20 μF and inductance 15 nH. The energy from each module is delivered through a vacuum insulator and a vacuum magneto-insulated coaxial line with inductance 6 nH and into a vacuum chamber inductance is 4 nH. In the vacuum chamber currents from all the modules are added by means of post-hole convolute to the coaxial gun, and among the electrodes of the gun a plasma-flow discharge is accelerated.

Overall inductance of the circuit is 25 nH that allows to reach 1μs time of PFS acceleration up to maximum value of magnetic energy in the circuit, that accounts for 87% of the facility energy storage. Power of the facility for the inductive store energizing will be > 810^{12} W. At that point PFS plasma velocity reaches 32.7 cm/μs and a peak current on the circuit-about 25 MA. According to literature data application of PFS as an inductive store switch will make it possible to increase the power of facility at the load 2-3 times by the reduction of the current rise time in the load as great as 10-20 fold and by the voltage increment by a factor of 2-5. In this case the power of the facility may reach (2-3)10^{13} W.

When the facility is used to accelerate plasma toroids with a frozen-in magnetic field plasma velocity up to 150 cm/μs may be obtained at the acceleration path 70 cm. For the chosen electrodes design, more than 60 % of facility energy is delivered in the kinetic plasma energy for 1.2 μs to accelerate toroids. The facility power on the acceleration of toroid reaches 510^{12}W. Expected energy density is more than 12 keV/nucleon.

For the facility to be used for the generation of a bremsstrahlung X-radiation it was offered to use 20 separated modules with a voltage pulse forming by means of plasma erosive switches. An individual electron diode is a

load for each module. According to our estimates at the module voltage 1 MV (500 kJ energy storage), a voltage pulse with an amplitude up to 2 MV and electron current up to 500 kA with 0.25 μs duration may be obtained at a separate diode. This is consistent with the total current of all 20 diodes of the facility about 10 MA and with the energy contribution to an electron beam of 3-4 MJ. Power of the facility reaches 210^{13} W.

In closing it may be said that the proposed design of the facility is based on fundamental principles of multimodule capacitive stores construction for powering inductive stores with plasma current switches which were checked in the process of the facility PIRIT-2 building and service (VNIIEF, Russia). This design possesses rather real characteristics obtained with other facilities in Russia and USA.

References.

1. M. P. Kalashnikov, P. V. Nickes, M. Schnuerer et. al. "X-ray L-spectra of plasma produced by picosecond laser at the intensities up to 10^{18} W/cm ^{2}" Abstract book, International Conference on Shot Wavelength Radiation and Applications, Zvenigorod, august 29-September 2. 1994.
2. Yonas G. , Electron beam induced pellet fusion, Sandia Report 74-5367.
3. C. W. Mendel J. P. Ouintenz, L. P. Mix, et al "15 cm hybrid ion diode on PBFA-1, J. Appl. Phys. 62 (9), 1 November (1987) pp. 3522-3534
4. A. I. Pavlovskii, N. P. Kolokolchikov, M. I. Dolotenko, et al. "Production of 15 MG magnetic fields in cascade ultrahigh field generators (MC-1) in "Megagauss Fields & Pulsed Power Systems", edited by V. M. Titov and G. A. Shvetsov Nova Science Publishers, New York, 1990. p. 29-32.
5. K. Whritham, B. T. Merrit, R. W. Holloway et al. "NOVA pulse power system description and status," Third IEEE International Power Conference. Albuquerque, N. M. June 1-3 1981- Dig. Techn. Pap., 1981, pp. 388-391.
6. W. L. Baker, G. Bird, I. S. Buff et al. " Multi-megaampere plasma flow switch driven liner implosions. " in "Megagauss Fields & Pulsed Power Systems" edited by V. M. Titov and G. A. Shvetsov Nova Science Publishers, New York, 1990. pp. 653-662
7. C. W. Mendel, J. P. Quintenz, L. P. Mix et al J. Appl. Phys., 62 (9), 1, Nov 1987, p 3522.
8. R. A. Meger, R. J. Comisso, G. Cooperstein and S. A. Goldstein, Appl. Phys. Lett., 42, 1983, p 943.

9. Pavlovskii A. I., Popkov N. F., Ryaslov E. A., Pikar A. S., Kargin V. I. et al. "Powerful pulsed energy source for plasma physics investigations" Conference MEGAGAUSS-6, Albuquerque, New Mexico (USA) 8-11 Nov. 1992 Abstract book p 207

10. S. P. Bugaev, A. M. Volkov, A. M. Iskol"dsky et al, IEEE Trans on PS., vol 18, No 1, Feb 1990, p 115.

11. B. Bernshtein, J. Smith, "AURORA", an electron accelerator"- IEEE Trans. on Nuclear Science, 1973, vol. NS-20, pp. 294 -299.

12. D. D. Bloomquist, R. W. Stinnet, D. H. McDaniel, J. R. Lee et al, Proc. of the 6-th IEEE Pulsed Power Conference, Arlington, VA edited by P. J. Turchi and B. H. Bernstein (IEEE, NY, 1987), p. 310

13. Maxwell Laboratories. "High-voltage capacitors", San-Diego. California 1967.

14. I. Smith, "Forming lines with liquid dielectric". Conference on Energy Storage, Compression and Switching, Torino, Italy, November 1974, pp. 25-39.

15. Pavlovskii A. I., Popkov N. F., Ryaslov E. A., Pikar A. S., Kargin V. I. et al. "Characteristic optimization of pulsed energy sources with plasma switches" Conference MEGAGAUSS-6, Albuquerque, New Mexico (USA) 8-11 Nov. 1992 Abstract book p 205

16. C. W. Mendel, Jr. and S. A. Goldstein, " A fast-opening switch for use in REB diode experiments" J. Appl. Phys. 1977, vol 52, p 1004-1009.

17. W. L. Baker, J. D. Beason, J. H. Degnan, K. E. Hackett, et al. "Plasma flow switch driven implosions", in [4], p. 615-622.

18. D. D. Hinshelwood, J. R. Booler, R. J. Commisso, G. Cooperstein, R. A. Meger, et al " Long conduction time plasma erosion switch experiment", Appl. Phys. Lett. Vol. 49, No. 24, 15 December 1986, p. 1635-1637.

19. R. E. Peterkin, Jr. I. Buff, M. H. Frese and N. F. Roderrick MACH2 "Simulations of plasma flow switches with shaped electrodes." in Megagauss Technology and Pulsed Power Applications., Edited by C. M. Fowler, R. S. Card and D. I. Erickson, Plenum Press, N. Y., 1987, pp. 551-558.

20. J. J. Ramirez, et al., "HERMES-III -a 16-TW, Shot pulse gamma ray simulator", Proc. 7-th International Conf. on High Power Particle Beams, Karlsruhe, Germany, July 4-8, 1988, pp. 148-157.

21. C. W. Mendel, et al., "A simple theory magnetic insulation from basic physical condition," Laser and Part. Beams, 1 part 3, (1983), p. 311

22. R. B. Spielman, T. W. Hussey, D. L. Halson, and S. F. Lopez "Multi-megagauss magnetic field generation on SATURN", in [4], pp. 43-53
23. D. Kortbawi, J. R. Goyer, F. K. Childers, and P. S. Sincerny, "Low jitter operation of a plasma opening switch, "Proceedings of the Ninth IEEE Pulsed Power Conference, 1994, p. 507-510.
24 P. Sincerny, S. Ashby, K. Childers, et al. "The DECADE high power generator," in [23] , pp. 880-883.
25. W. Rix, A. R. Miller, D. Husovsky, J. Tompson, and E. Waisman, "Status of the ACE-4 inductive storage technology, 6 MA driver," in [23] pp. 115-118.
26. J. Tompson, D. Husovsky, A. R. Miller, W. Rix, and E. Waisman, "ACE-4 microsecond plasma opening switch and plasma filled load characterization," in [23] pp. 119-122.
27. G. B. Frazier et al. OWL-II Generator of impulse electron beam - I. Vac. Sci. Technol., 1975, vol 12, N6, pp. 1183-1187.
28. C High energy pulse power development and application to fast imploding plasma liners in "Ultrahigh magnetic field," V. M. Titov and G. A. Shvetsov, eds, Nauka (1984), pp. 39-49
29. M. E. Savage, W. W. Simpson, and M. A. Usher, "Results from long conduction time plasma opening switch experiments at Sandia National Laboratories," in [23] pp. 110-114.
30. R. P. Shurter, R. L. Carlson, and J. G. Melton, "Investigations of the electrical breakdown properties of insulator materials used in high voltage vacuum diodes," in [23] pp. 249-252.
31. J. Thompson, D. Husovsky, A. R. Miller, K. Robertson, R. Ingermanson, and D. Parks, "Flashboard plasma source characterization for microsecond plasma opening switches," in [23] pp. 524-527.
32. R. L. Browers, A. E. Greene, D. L. Peterson, and N. F. Roderick, "Computer modeling of plasma flow switches - high current switching on PROCYON, in [23] , pp. 538-541.
33. P. J. Goodrich, D. D. Hinshelwood, R. J. Commisso, J. M. Grossmann, J. C. Kellogg, and B. V. Weber, "High power opening switch operation on HAWK, " in [23] , pp. 511-515.
34. W. Clark, M. Gersten, J. Katzenstein, et al, "aluminum, and titanium imploding plasma experiments on the BLACKJACK-5 pulse generator" J. Appl. Phys. 53(6) June 1982 p 4099-4104

35. T. W. L. Sanford, J. R. Lee, J. A. Halbleib et al "Electron flow and impedance of an 18-blade frustum diode" J. Appl. Phys. 59(11) June 1986 p 3868-3880

36. E. Waisman and M. Chapman "Vacuum transmission lines in the presence of a resistive cathode plasma" J. Appl. Phys. 53(1) January 1982 p 724-730

37. J. P. VanDevender, D. H. McDaniel, E. L. Neau et al "Magnetic inhibition of insulator flashover" J. Appl. Phys. 53(6) June 1982 p 4441-4447

38. Physics International Inc., San Leandro CA, Reports Nos. PIIR-1-80 and PIIR-2-80.